Chapter 9

Heat Balance

Heat Balances of Kilns and Coolers and Related Topics

Th. Richner / A. Obrist
PT 99/14496/E (update of VA 8/5180/E)

1. INTRODUCTION ... 488
2. OVERVIEW OF COMPLETE HEAT BALANCE PROCEDURE ... 488
  2.1 Why to do a Heat Balance? ... 488
  2.2 How to Proceed ... 489
3. BASIS OF BALANCE AND REMARKS REGARDING EXECUTION ... 490
  3.1 Balance Limits ... 490
  3.2 Guidelines for Test Duration ... 492
  3.3 Kiln Operation ... 492
  3.4 Kiln Data ... 492
4. HEAT BALANCE CALCULATIONS ... 493
  4.1 General Remarks ... 493
  4.2 Determination of Clinker Production ... 495
  4.3 Heat from Fuel ... 501
  4.4 Burnable Components in Raw Material ... 502
  4.5 Loss due to Incomplete Combustion ... 503
  4.6 Heat of Formation ... 503
  4.7 Heat due to Partly Decarbonized Material ... 504
  4.8 Heat of Evaporation ... 506
  4.9 Sensible Heat ... 507
  4.10 Heat Loss due to Radiation and Convection ... 510
5. HEAT BALANCES ... 519
  5.1 General ... 519
  5.2 Examples of Heat Balances of Various Kiln Systems ... 521
6. SPECIAL PART ... 523
  6.1 Influence of Reference Temperature ... 523
  6.2 Heat of Formation ... 526
  6.3 Radiation Heat Transfer ... 530
  6.4 Convective Heat Transfer ... 531
  6.5 Effect of Thermal Improvements ... 535
  6.6 Heat Transfer in Preheaters and Coolers and Improvement Potential ... 537
7. TEST QUESTIONS ... 542

8. LITERATURE 543
9. SYMBOLS AND UNITS 544

SUMMARY

A heat balance is an efficient tool to measure the actual state of a kiln system. It allows a better assessment of the heat consumption and reveals the potentials for improvements (regarding the thermal aspects).

The principle of a heat balance is rather simple: we select our system limits for the balance and measure all inputs and outputs.

After the necessary measuring campaign we need to calculate the various heat items, e.g.:

- Heat of fuel combustion
- Combustibles in raw meal or exhaust gas
- Heat of formation
- Heat of evaporation
- Sensible heats of all gas and mass flows
- Radiation and convection heat

The heat balance shows clearly how the heat is spent among the individual items. This information is therefore most suitable to detect abnormal operating conditions or potential for improvements. As a next step we can decide which practical measures should be taken in order to achieve improvements in the thermal energy consumption.

When improvements are realized we can often take into account that the saving of fuel is by a factor of 1.3 to 1.5 higher than the primary improvements on the balance item (multiplication factor), as long as we consider the high temperature zone.

Considerable improvements can be realized by reducing shell losses, false air inleaks, heat exchange in certain preheater types and in clinker coolers.

1. INTRODUCTION

Heat balances on a kiln system can offer extremely useful information on the thermal performance of the system. Heat balances show where or how the fuel heat is consumed, based on the simple principle of:

input = output

Unnecessary energy losses can be easily detected.

The principle aim of this chapter is to serve a practical guide for doing heat balances on cement kilns. It can be used as working paper and does neither require special thermodynamic knowledge nor supplementary literature or tables.

For the more interested reader some special aspects are treated in a separate chapter.

The principle of heat balance may be easily transferred to other systems such as preheaters, coolers and drying systems. Therefore the use of this chapter can be extended to other systems than cement kilns.

In this chapter, only SI units are used, which means that heat is always given in kJ (kilo Joule). Conversion calculations within the chapter will no more be required. Incidentally this may also contribute to the consequent use of SI units.

2. OVERVIEW OF COMPLETE HEAT BALANCE PROCEDURE

2.1 Why to do a Heat Balance?

Various reasons or circumstances may cause a need for a heat balance measurement. The following situations may justify a heat balance:

- Performance test
- Recording of kiln performance before/after a modification
- Unusually high heat consumption or abnormal kiln operational data
- Kiln optimization campaign

It may be self explaining that an extensive heat balance also costs money, especially if a large number of people are involved. Therefore the costs may be put in relation to the obtainable benefits. A potential improvement of say 100 kJ/kg of heat consumption on a 3000 t/d kiln means a savings in the order of US$ 200'000 per year (at current fuel prices). In such a case it may be worthwhile to invest some money for a detailed investigation including a complete heat balance.

Although the specific heat consumption proper could also be determined by measuring nothing but fuel heat and clinker production, a complete heat balance does offer considerably more information and security. The consistency of the measured data is proved much better, and the balance shows clearly where the heat is consumed. A heat balance is obviously a very efficient tool for assessment of thermal efficiency.

2.2 How to Proceed

A heat balance does not only mean calculation of heat balance items. The complete procedure usually includes the following steps:

2.2.1 1st Step: Preparation

The extent of works to be done depends on the completeness and reliability which is desired. A careful planning and preparation is recommendable. The following basic items must be clarified:

- What has to be measured (kind and location of measuring / sampling points)?
- Duration of test?
- Frequency of measurements (continuous recording, spot measurements, time intervals, etc.)?

Under above preconditions the number of people required and the necessary measuring equipment can be determined. Temporary equipment may usually become necessary, whereas the existing permanent instrumentation should be carefully checked and calibrated.

The following list may be used as checklist for a test preparation:

- People available for test period?
- Does everybody know what to do at what time?
- Necessary logsheets for manual recordings ready?
- Data recording system (electronic, pen recorder, etc.) available?
- Flow of information among test team?
- Calibration or checks of instruments and scales done (flowmeters, orifice plates, venturis, dp-cells, thermocouples, etc.)?
- Temporary measuring equipment available? Complete? Correct span? Functionning properly?
  For example:
    - pitot tube
    - U-tube manometer / electronic manometer
    - mobile thermometer
    - radiation pyrometer
    - gas analyzer / Orsat
    - sampling equipment for gas
- Sampling procedure for solids (e.g. meal, dust, clinker) clarified?
- Analyzing facilities?

2.2.2 2nd Step: Execution

An important precondition for a good test is a steady kiln operation. The test should only be started if the system has reached a constant equilibrium state. During the test, variations of operating parameters should be avoided.

For the measuring techniques reference is made to the corresponding chapter.

It is recommended to check completeness and reliability of measurements already during the test, afterwards missing or uncertain information may create problems at the final evaluation.

2.2.3 3rd Step: Evaluation

This step is the main scope of this chapter. Evaluation of data means to establish a heat balance calculation according to the principle

"input = output".

2.2.4 4th Step: Discussion

A heat balance as such must bring some practical conclusions otherwise it would be only of academical interest. The following items may be considered:

- Acceptable (normal) heat consumption?
- Are heat balance items normal for given kiln systems?
- Measures in order to improve heat economy of the system?

The last item can become quite an extensive work and the economical feasibility must be considered as well. Such subjects, however, are beyond the scope of this chapter.

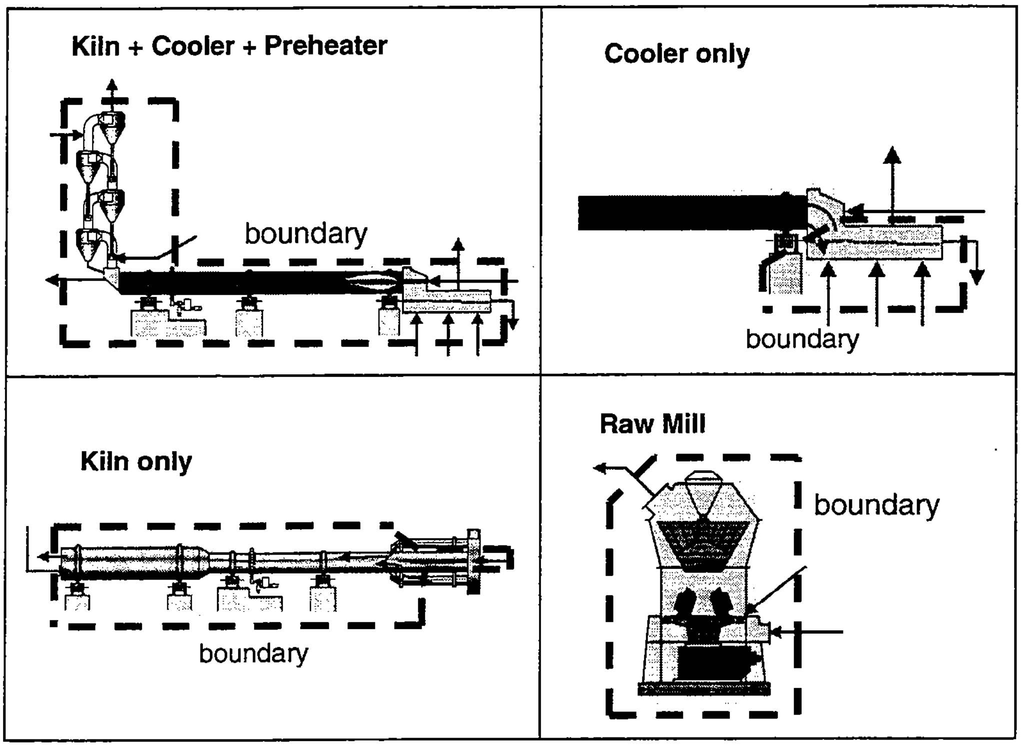
Note: Summarizing, it is obvious that the 3rd step „Evaluation" is only a limited part in the whole context.

3. BASIS OF BALANCE AND REMARKS REGARDING EXECUTION

3.1 Balance Limits

In many balance reports the boundary for the balance is not shown expressively. As long as „standard cases" are considered it may sometimes seem evident how the balance limits were selected. Nevertheless it is advantageous to indicate always clearly where the boundary for the balance is. This will avoid misunderstandings and reduce error possibilities. For that purpose a (simplified) flowsheet is required. In this scheme the boundary must be marked by a line which envelopes the system under consideration. When a measuring campaign in a plant is planned such definitions should be made already in the planning phase, i.e before the test.

Fig. 1 **Examples of Balance Boundaries**



The boundary generates various cutpoints with ingoing or outgoing solid- and gas streams. Likewise radiation and convection heat crosses the boundary.

Each cutpoint means a certain item in the heat balance because it represents a heat flow either into or out of the system.

By this measure the system is clearly defined and nothing can be forgotten.

Basically, any shape of the boundary could theoretically be chosen. To give an extreme example: The boundary could even cut a rotary kiln at half length! However, the boundary must be selected according to practical considerations. This means that the cutpoints which are generated must be:

- easily accessible for reliable measurements
- of practical interest in the whole context.

3.2 Guidelines for Test Duration

A long test duration would allow for a good accuracy but the available time is limited by practical considerations.

As a rough guideline the minimum test duration should be about ten times the material retention time in the complete kiln system:

- test duration = 10 x retention time

Other factors like regularity of kiln operation also influence the test duration. If the process is very unsteady longer times should be envisaged.

On a normal suspension preheater kiln the retention time of the material is in the order of one hour. In contrast, on a lime shaft kiln retention times above 24 hours may occur. Therefore the necessary test durations for these two cases must be completely different.

Although test durations must be set individually the following list may be used as rough guideline:

Type of Kiln	**Test Duration (hours) for Heat Balance**
Suspension preheater kiln with precalciner	12
Suspension preheater kiln without precalciner	12 to 24
Long dry / wet kiln	24

3.3 Kiln Operation

During the test, the kiln must run at constant and steady conditions. Changing of setpoints should be avoided whenever possible.

Interruptions have to be logged. If serious problems occur, the test has to be extended or even postponed. Therefore it is often worthwhile to plan a certain time reserve.

From a theoretical point of view a proper balance can only be made if the system runs at steady conditions. E.g. during heating-up heat is stored in the system and there is no balance between input and output (input > output).

3.4 Kiln Data

In order to facilitate the final discussion it is usually necessary to collect the main data of the system such as:

a) System
  * process
  * type of kiln
  * nominal capacity
  * type of preheater / precalciner
  * type of cooler
  * supplier
  * year of commissioning
  * fuel and firing system
  * type of burner nozzle
  * dust reintroduction system
  * dimensions of main equipment (sizes, inclinations, etc.)
  * data on fans, derives, etc.

b) Operation
   - various operating data (rpm, kW, temperature and pressure profiles along kiln system, grate speed, undergrate pressures, etc.)
   - electric power readings (before / after test)
   - chemical analysis of raw meal, dust(s) and clinker, LSF, SR, AR, etc.

Above data are not necessarily required for heat balance calculations proper, but they should be included in a complete balance report in order to describe the system and to give more information on its performance.

4. HEAT BALANCE CALCULATIONS

4.1 General Remarks

4.1.1 Symbols and Units

A		m^2	area
C_R		W/m^2K^4	radiation constant
c_P		kJ/kg C	specific heat (at const. pressure),
	or	kJ/Nm^3 C	specific heat capacity
CV		kJ/kg	calorific value
D		m	diameter
g		m/s^2	gravity constant
h		kJ/kg	heat content (specific)
	or	kJ/Nm^3	
	or	kJ/kg cli	
L		m	length
m		kg	mass
	or	kg/kg	specific mass
m_f		kg/h	mass flow
Q_f		kW	heat flow (1 kW = 1 kJ/s)
t		C	temperature (Centigrade)
T		K	temperature (Kelvin)
v		m/s	velocity
w		kg/kg	water content
Greek Letters			
∝		W/m^2K	heat transfer coefficient
ε		-	emissivity (for radiation)
λ		W/m C	heat conductivity
ρ		kg/m^3	density

Dimensionless Numbers

Nu	Nusselt number (for heat transfer)
Pr	Prandtl number
R	kiln feed (raw meal) / clinker-ratio
Re	Reynolds number

Indices

conv	convection
rad	radiation
tot	total
o	ambient condition or zero condition

Conversion Factors

Length	1 inch	0.0254 m
	1 ft	0.3048 m
Area	1 sq. ft	0.092903 m^2
Volume, Volume Flow	1 cu.ft	0.028316 m^3
	1 cu.ft/min	1.699 m^3/h (actual m^3)
Mass	1 lb.	0.45359 kg
	1 short ton (USA)	907.185 kg
Pressure	1 bar	10^5 N/m^2
	1 mm H_2O-Col.	9.806 N/m^2
	1 atm.	1.013 bar
Energy	1 kJ	1000 J
	1 MJ	1000 kJ
	1 kWh	3600 kJ
	1 kcal	4.187 kJ
	1 BTU	1.055 kJ
Temperature Conversion	C =	5/9(F - 32)
	K =	273.15 + C
Heat Flow	1 kW	1000 W = 1 kJ/s
	1 kcal/h	1.163 W
	1 BTU/h	0.29307 W
Specific Heat	1 kcal/kg C	4.187 kJ/kg C = 4187 J/kg C
	1 BTU/lb F	1 kcal/kg C = 4.187 kJ/kg C
Heat Transfer Coeffic.	1 $kcal/m^2h$ C	1.163 W/m^2 C
	1 BTU/ft^2h F	5.678 W/m^2C
Standard Conditions for Gases	Standard Conditions	0°C and 1 atm (1.013 bar)

$$Nm^3 = act.m^3 \times \frac{273.15}{273.16 + t(C)} \times \frac{p(bar)}{1.013bar}$$

4.1.2 Reference Temperature

We will set the usual reference temperature to 20°C i.e. the sensible heat of mass flows at 20°C becomes zero.

All „heats of transformation“ such as combustion, evaporation, formation are also based on 20°C reference.

4.1.3 Input / Output

Whether a heat item represents an input or output is determined by the direction of mass flow, according to:

- into boundary = input
- out of boundary = output

This is a simple and useful convention (not a natural law).

If „heats of transformation“ occur within the boundary the net heat effect is normally used as criterion:

- heat producing process = input
- heat consuming process = output

A heat producing process is e.g. the fuel combustion (exothermic).

4.1.4 Reference Quantity

The heat balance is referred to 1 kg of clinker produced. This requires a general calculation step (division by clinker production) which is not shown in the following formulas in order to maintain a more simple presentation.

4.2 Determination of Clinker Production

4.2.1 General

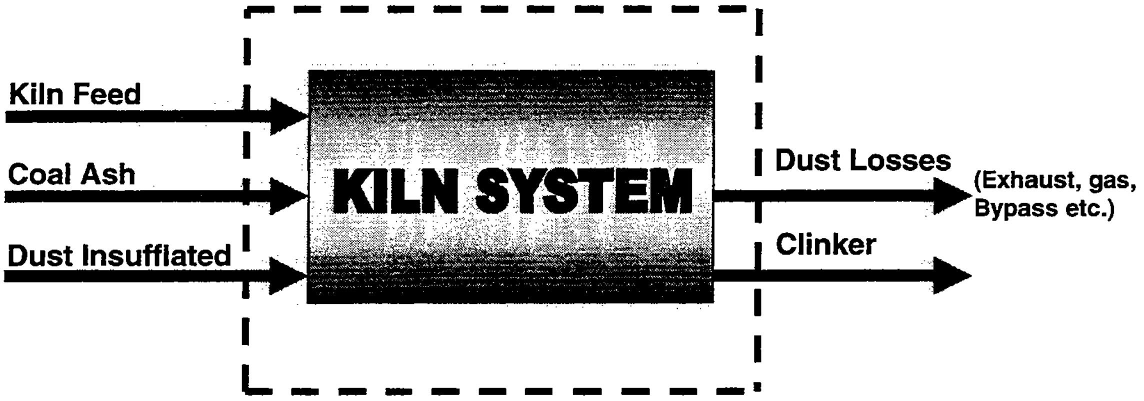
The clinker production during a test is a key figure for all the following calculations. We will refer all flows and heats to 1 kg of clinker produced.

Determination of clinker production can be made by direct weighing of the production which is by far the best method. If this can be done the following chapter 4.2.2 can be ignored. But in some cases no direct measurement is possible. Therefore, an indirect determination may be necessary as shown in the following.

4.2.2 Indirect Determination

It is well known, that from approx. 1.56 kg raw material (not kiln feed!) 1 kg clinker can be produced. Starting from this fact it seems to be easily possible to calculate the clinker production. However, the above factor of 1.56 if of limited practical help because it can be superimposed by dust return and depends on some other influences.

The best method in such a case is to establish a mass balance for the system. Similar to a heat balance a boundary for a mass balance can be defined. Thus the clinker production becomes:



Boundary for mass balance

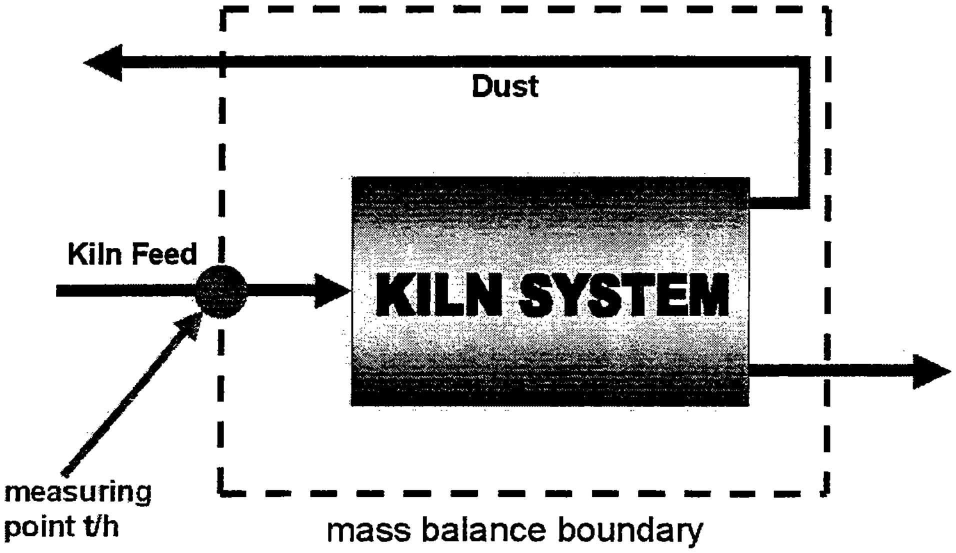
$$\text{Clinker} = \left\{ \begin{array}{l} + \text{kiln feed} \\ + \text{coal ash} \\ + \text{dust insufflated} \\ - \text{dust losses} \\ \end{array} \right\} \quad \text{all calculated on } \underline{\text{L.o.I. free}} \text{ basis!}$$

This principle is quite simple. The following additional remarks can be given:

- The boundary for the mass balance does not necessarily have to coincide with the heat balance boundary.
- The mass balance boundary must cut the kiln feed measuring point (because the mass flow is known at this point).
- The balance is always made on a loss-on-ignition-free (L.o.I.-free) base (no balance for the entire quantity including L.o.I. can be made since part of it is converted to gas, which is not included here).

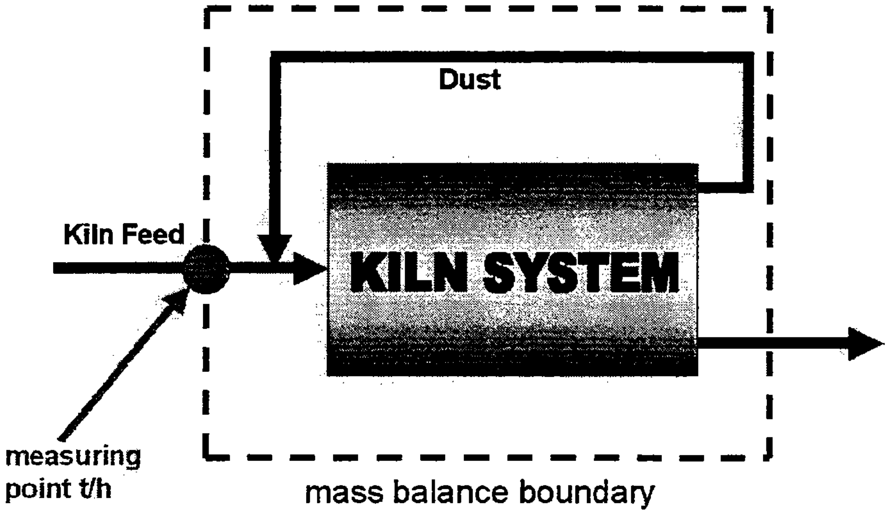
Regarding only the dust loss from the exhaust gas there are two basic possibilities:

a) Dust Flow crosses mass balance boundary



- mass balance is influenced by dust flow
- note that is <u>not</u> significant whether or how the dust is returned (outside the boundary)!

b) Dust flow does <u>not</u> leave mass balance boundary (<u>internal</u> dust return)



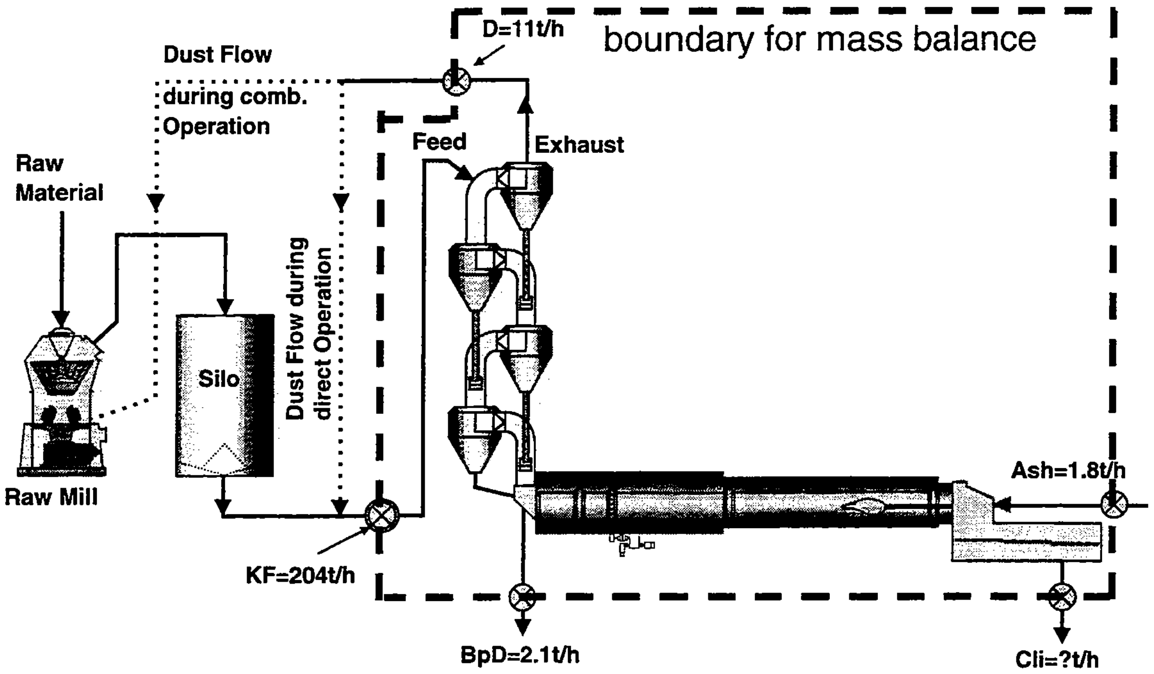
- mass balance is <u>not</u> influenced by dust flow
- internal dust return must be steady, i.e. no storage being built up (silos!)

Two practical examples illustrating above two cases are shown in the following.

4.2.3 Examples

a) External Dust Recirculation (outside of boundary)

Fig. 2 **Mass Balance / External Dust Recirculation**

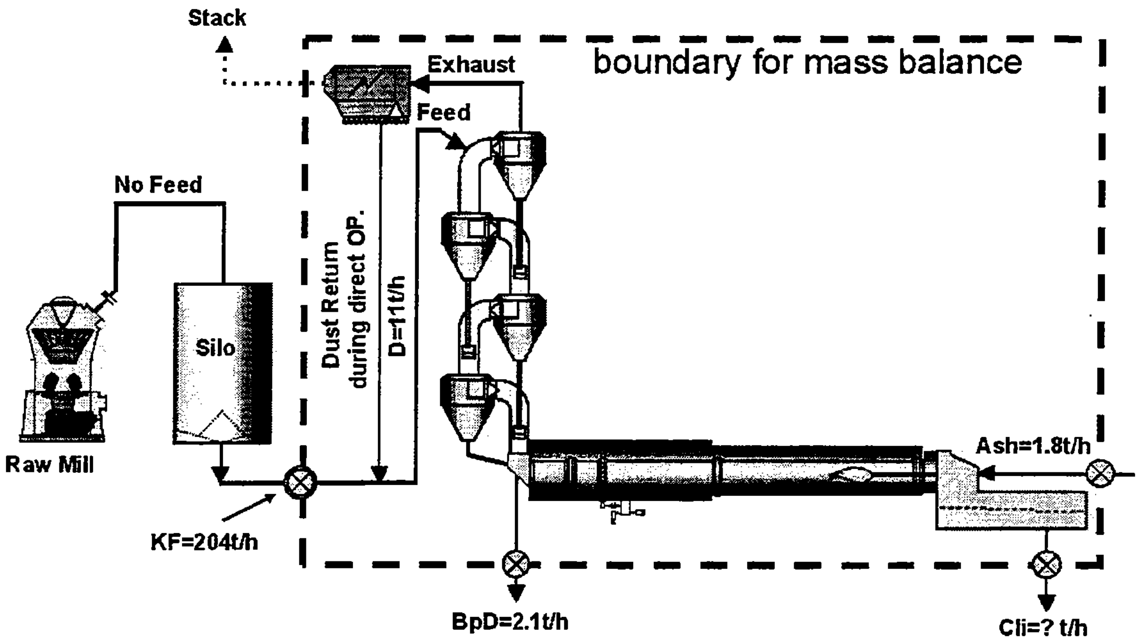


	m_f (dry) [t/h]	L.o.I. [-]	m_f (1-L.o.I.) [t/h]
Kiln Feed (KF)	204.0	0.357	131.17
Coal Ash (Ash)	1.8	~ 0	+ 1.80
Dust in Exhaust (D)	11.0	0.315	- 7.54
Bypass Dust (BpD)	2.1	0.070	- 1.95
Clinker (Cli)		~ 0	**123.48 t/h**

Note that the kiln feed data (L.o.I.) may slightly change when going from combined operation to direct operation or vice versa!

Kiln Feed / Clinker = R = 204.0 / 123.48 = **1.652** (all included) b1) Internal Dust Recirculation (inside of boundary)

Fig. 3 **Mass Balance / Internal Dust Recirculation**



During direct operation the following calculation method applies:

	m_f (dry) [t/h]	L.o.I. [-]	m_f (1-L.o.I.) [t/h]
Kiln Feed (KF)	204.0	0.357	131.17
Coal Ash (Ash)	1.8	~ 0	+ 1.80
Bypass Dust (BpD)	2.1	0.070	- 1.95
Clinker (Cli)		~ 0	**131.02 t/h**

Kiln Feed/Clinker = R = 204.0/131.02 = **1.557**

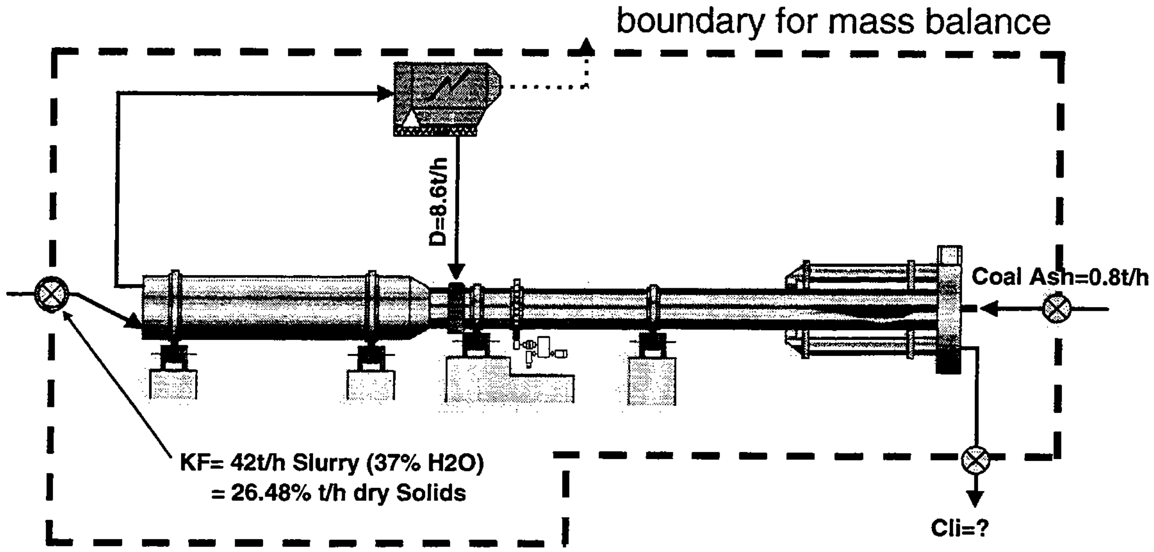
Note the difference to example a)!

Incidentally the example b1) is shown for comparison to example a) and does by no means represent a superior solution of the dust return!

The following example b2) shows a very similar way of calculation to example b1).

b2) Internal Dust Return (wet kiln)

Fig. 4 **Mass Balance / Internal Dust Recirculation**



	m_f (wet) [t/h]	m_f (dry) [t/h]	L.o.I. [-]	m_f (1-L.o.I.) [t/h]
Kiln Feed (KF)	42	26.46	0.360	16.93
Coal Ash (Ash)	-	0.8	~ 0	0.8
Clinker			~ 0	**17.73 t/h**

4.3 Heat from Fuel

4.3.1 Fuel Firing

Fuel can be introduced at the following locations:

- Kiln firing
- Secondary firing or precalciner
- Burnable components in raw meal

Generally the heat from fuel is calculated:

$$\underline{h = m \cdot CV} \qquad \text{(kJ/kg cli)}$$

h = heat (kJ/kg cli)

m = specific fuel consumption (kg/kg cli <u>or</u> Nm^3/kg cli)

CV = calorific value (kJ/kg fuel or kJ/Nm^3 fuel)

For the calorific value CV only the low (or net) value is used within the „Holderbank" Group (for conversion see chapter „Combustion Engineering").

Heat balance referring to high (or gross) heat value are sometimes encountered. But here an important note must be made: the use of high heat values is based on a quite different method of considering heat losses. Therefore those balances cannot be compared directly to our type of balance.

4.3.2 Coal Firing

For coal firing it is essential that the CV and the consumption (m) refer both to the same conditions. The normal convention is to refer to the state as fed to the kiln burner.

The state as fed to burner may sometimes be different from the state as analyzed. Differences can occur because of dust addition in coal mill, loss of volatile matter or just simply by changed moisture conditions.

If the actual CV at the given coal moisture w is not known it can be calculated from the value CV_o at the moisture w_o:

$$\underline{CV = [(1-w) / (1-w_0)] \cdot (CV_0 + w_0 \cdot r) - w \cdot r}$$

where: r = 2450 kJ/kg

= heat of water evaporation at reference temperature 20°C

w, w_o = weight fractions of water

Examples:

a) Coal, CV at 5% moisture = 26'500 kJ/kg
CV at 1% moisture (as fed to burner) = ?

$CV = [(1-0.01) / (1-0.05)] \cdot (26500 + 0.05 \cdot 2450) - 0.01 \cdot 2.450$

$CV = \underline{27'464\ kJ/kg}$

If above coal (1% moisture) is fired at a specific rate of 0.1230 kg/kg cli:

$h = 0.1230 \cdot 27'464 = \underline{3'378\ kJ/kg\ cli}$

b) If the CV for dry matter is known (CV_{dry}) the general formula can be simplified (for w_o = 0):

$\underline{CV = (1 - w)\ CV_{dry} - w \cdot r}$

CV_{dry} = 28 MJ/kg, moisture 2%

$CV = 28 \cdot (1 - 0.02) - 0.02 \cdot 2.45 = \underline{27.39\ MJ/kg}$

4.4 Burnable Components in Raw Material

4.4.1 Organic Matter

Organic matter can be present in the raw meal e.g. in form of oil shale or exceptionally even in form of free crude oil.

Such material is partly volatilized in the preheating zone and leaves the system partly as unburnt light hydrocarbons. If the latter are actually measured and considered in the total heat balance it is recommended to determine the calorific value of the raw meal (not directly, but by extracting its organic matter). Thus the heat input becomes:

$\underline{h = CV_{low} \cdot R}$ (kJ/kg cli)

where:

CV_{low} = calorific value due to organic matter, referred to 1 kg raw meal

R = kiln feed / clinker - factor

If light hydrocarbons in the exhaust gas are not measured nor considered in the total heat balance anyway the following approach will produce better results:

Determine the organic content only (org. C, measured by burning in pure O_2 to CO_2). Then consider exclusively the organic C (the rest can be neglected). The approximate heat input becomes:

$\underline{h = C \cdot R \cdot 33'000\ kJ/kg}$ (kJ/kg cli)

where

C = organic carbon content in raw meal

Above mentioned is only an approximation but often used due to its simplicity.

Example:

R = 1.6 kg/kg cli, C = 0.2% carbon

$q = 0.002 \cdot 1.6 \cdot 33'000 = \underline{106\ kJ/kg\ cli}$

4.4.2 Inorganic Matter

In certain cases residues of non-oxidized pyrite (FeS_2) can occur in the raw meal. The heat input becomes:

$h = S \cdot R \cdot 12'930$ kJ/kg (kJ/kg cli)

where

S = weight fraction of sulfur (expressed as S!) from pyrite in raw meal

Example:

R = 1.6 kg/kg cli, 0.05% S (from pyrite) in raw meal

h = $0.0005 \cdot 1.6 \cdot 12'930 =$ 10 kJ/kg cli

The practical heat effect in the above case is only marginal.

4.5 Loss due to Incomplete Combustion

If unburnt gases such as CO, H_2, CH_4 occur in the exhaust gas an additional heat output occurs.

The loss can be calculated to:

h = $m \cdot (CO \cdot 12'640 + H_2 \cdot 10'800 + CH_4 \cdot 35'840)$ (kJ/kg cli)

m = specific gas quantity (Nm^3/kg cli)

CO, H_2, CH_4 = volume fractions in exhaust (referred to wet gas)

In most cases only CO is measured and then the calculation becomes:

$h = m \cdot CO \cdot 12'640$ (kJ/kg cli)

Example

m = 1.50 Nm^3/kg cli (SP kiln)

CO = 0.2% (ref to wet)

q = $1.50 \cdot 0.002 \cdot 12'640 =$ 38 kJ/kg cli

4.6 Heat of Formation

The heat of formation takes into account all main reactions which occur when raw meal is transformed to clinker, as follows:

RAW MEAL

- Heat of dehydration of clay (endothermic)
- Heat of decarbonation of $CaCO_3 + MgCO_3$ (endothermic)
- Heat of formation of clinker (exothermic!)

CLINKER

In most of the practical cases it is sufficient to assume a constant value of

h = 1750 kJ/kg cli

The value mentioned before represents a heat output since the overall reaction is endothermic (heat consuming). The main contribution to the overall value comes from the decarbonation of $CaCO_3$ (approx. 2100 kJ/kg cli).

The heat of formation may naturally have some variations from one raw meal to the other. But due to the narrow range which is specified for the cement clinker composition no major deviations (of say more than +/- 50 kJ/kg cli) have to be expected in normal cases.

If the CaO in clinker does not originate from $CaCO_3$, but from raw material sources containing less CO_2 than the CaO balance (such as coal ash or partly decarbonized raw mix) the heat of formation would theoretically change. However, this problem can be easily avoided by the following definition:

- All mass flows (as kiln feed, dust losses, coal ash) which carry a certain amount of CaO not coming from $CaCO_3$ are considered as „heat flows" according to their „non-carbonatic" CaO content (see chapter 4.7).

By following the above definition it is not necessary to make alterations at the heat of formation. An „abnormal" situation can simply be treated by creating additional inputs or outputs, but not by changing the „standard" heat of formation.

The procedure is based on the idea of an „ideal" clinker burning from pure carbonates. If those ideal conditions do not apply we set corrections in the corresponding heat inputs or outputs. Such principles are well known from calculation of bypass CaO-losses.

Additional information on the heat of formation is given in chapter 6.2.

4.7 Heat due to Partly Decarbonized Material

Decomposition of carbonates in an essential heat effect in a cement kiln. Usually one thinks of the two extreme cases of either complete presence of carbonates ($CaCO_3$, $MgCO_3$) or complete absence of carbonates (e.g. clinker). But there can also be cases in between which influence the heat balance.

Material streams can transport non-sensible heat due to partly decarbonized material (CaO) or non-carbonatic CaO. The following possibilities exist:

1) raw meal (containing e.g. CaO free or non carbonatic, CaO-bearing minerals)
2) exhaust gas dust (partly decarbonized)
3) bypass dust (largely decarbonized)
4) coal ash

The heat can either be negative or positive according to the direction of flow (ingoing or outgoing).

If item 2) (exhaust gas) is considered in the balance it is essential to consider also item 1) (raw meal)! In many cases kiln dust (which contains some free CaO) is returned to the kiln but not necessarily at exactly the same rate as the outcoming dust (e.g. on a system combined with raw mill, alternating between combined and direct operation). Even if dust is returned the net heat effect of item 1) minus item 2) may not automatically be zero!

If the CaO and CO_2 is known from chemical analysis the non carbonatic part CaO_{nc} can be calculated:

$$\underline{CaO_{nc} = CaO - (56 / 44)\, CO_2}$$

Strictly speaking, above formula is only correct if no other carbonates than $CaCO_3$ occur. If $MgCO_3$ is present in form of carbonates the „carbonatic MgO" has to be taken into account:

$$CaO_{nc} = CaO - 56\, [(CO_2/44) - (MgO/40)]$$

Thus the heat is calculated to

$$\underline{h = m \cdot CaO_{nc} \cdot 3150} \qquad \text{(kJ/kg cli)}$$

m = spec. mass (kg/kg cli)

CaO_{nc} = „non-carbonatic" CaO, expresses as weight fraction

Above formula does not consider the small possible influence of $MgCO_3$ decarbonation heat. If the assumption can be made that all MgO occurs in non-carbonatic form (e.g. after a heat treatment in the 700°C range) the following improved formula can be applied:

$h = m\ (CaO_{nc}\ .\ 3150 + MgO\ .\ 2710)$ (kJ/kg cli)

Examples

1) Raw Meal and Kiln Dust

(dust returned, measurements refer to balance limits, normal raw mix)

Raw Meal	**Kiln Dust**
R = 1.65 kg/kg cli CaO = 42.3% MgO = 0.9% CO_2 = 34.0%	m = 0.09 kg/kg cli CaO = 43.5% MgO = 1.1% CO_2 = 30.5%
CaO_{nc} = 42.3-56 [(34/44) - (0.9/40) = 0.3%	CaO_{nc} = 43.5-56 [(30.5/44) - (1.1/40) = 6.2%
h = 1.65 · 0.003 · 3150 = **16 kJ/kg cli (input)**	h = 0.09 · 0.062 · 3150 = **18 kJ/kg cli (output)**

In the above example the net heat effect is virtually zero and may be completely neglected. But this may not be used as a general rule as shown by the next example.

2) Raw Meal and Kiln Dust

(similar to example 1), but raw mix containing a major proportion of non-carbonatic CaO)

Raw Meal	**Kiln Dust**
R = 1.60 kg/kg cli CaO = 43.2% MgO = 0.9% CO_2 = 30.0%	m = 0.09 kg/kg cli CaO = 43.5% MgO = 1.1% CO_2 = 30.5%
CaO_{nc} = 43.2-56 [(30/44) - (0.9/40) = 6.28%	CaO_{nc} = 43.5-56 [(30.5/44) - (1.1/40) = 6.2%
h = 1.60 · 0.0628 · 3150 = **317 kJ/kg cli (input)**	h = 0.09 · 0.062 · 3150 = **18 kJ/kg cli (output)**

Although non-carbonatic CaO occurs seldom, it may largely contribute to the heat balance (in the latter example a net effect of 299 kJ/kg cli!). The practical problem, however, is to determine the CaO_{nc} with sufficient precision.

3) Bypass Dust

m = 0.04 kg/kg cli (quantity of bypass dust)
CaO = 56.2%
MgO = 1.0%
CO_2 = 1.8%
CaO_{nc} = 56.2 - (56/44) * 1.8 = 53.9%
q = 0.04 * 0.539 * 3150 + 0.01 * 2710 = <u>95 kJ/kg cli</u> (output)

4) Coal Ash

m = 0.02 kg/kg cli (quantity of ash)
CaO = 21%
MgO = 2%
q = 0.02 (0.21 * 3150 + 0.02 * 2710) = <u>14 kJ/kg cli</u> (input)

4.8 Heat of Evaporation

If water is evaporated within the balance limits the heat of evaporation becomes

$\underline{h = m \cdot 2450}$ (kJ/kg cli)

m = evaporated water (kg/kg cli)

Above items means an output. A large source of water evaporation is usually the slurry feed to a wet kiln.

Although the calculation of heat of evaporation is obviously simple a few notes are given:

- Only the <u>free</u> water of the kiln feed is considered (the hydrate water is already included in the heat of formation!).
- Water evaporation can also be caused by water injection into preheater, kiln, cooler, etc.
- The water evaporated from the fuel must <u>not</u> be included (this effect is already included in the net heat value, provided it has been determined as described in paragraph 4.3).

<u>Examples</u>

a) Wet Kiln: slurry water content = 35%

R = 1.56 kg/kg cli (dry)
m = $0.35 / (1-0.35) \cdot 1.56$ = 0.84 kg/kg cli
h = $0.84 \cdot 2450$ = <u>2058 kJ/kg cli</u>

b) Water Spray into Planetary Cooler

m = 0.05 kg/kg cli
h = 0.05 * 2450 = <u>123 kJ/kg cli</u>

4.9 Sensible Heat

4.9.1 General

Generally the sensible heats are calculated as follows:

$h = m \cdot c_p \cdot (t - 20°C)$ (kJ/kg cli)

m = specific mass (kg/kg cli or Nm^3/kg cli)

c_p = average specific heat (kJ/kg C or kJ/Nm^3 C)

t = temperature of m (C)

Above formula uses a reference temperature of 20°C, i.e. sensible heats of material and gas flows at 20°C are zero.

The value h (kJ/kg cli) can either be positive (if $t > 20°C$) or negative (if $t < 20°C$).

Whether h represents an input or an output (see 4.1) depends only on the direction of the flow „m“:

- if m = entering boundary → h = input
- if m = leaving boundary → h = output

Basically the value m can be expressed as kg or Nm^3. It is then logical that the c_p values used must also refer to same unit (per kg or per Nm^3).

For convenience we use the following convention:

- for solid flows → unit = kg
- for gaseous flows → unit = Nm^3 [1)]

[1)] The application of the unit „kg“ for gases would also be thinkable and would even facilitate the mass balance calculations. But since Nm^3 is well established in the cement industry and since the cp-diagrams refer to Nm^3 only, Nm^3 is used in this chapter.

The necessary c_p values are to be found in the diagrams Fig. 5 and 6 (for solids and fuels) and Fig. 7 (for gases).

The same basic mode of calculation of sensible heat can be adapted for all material and gas flows crossing the boundary such as:

- Raw meal
- Clinker
- Dust(s)
- Exhaust gas, bypass gas, waste gas, etc.
- Cooling air, false air, etc.

Fig. 5 Cp of Solids

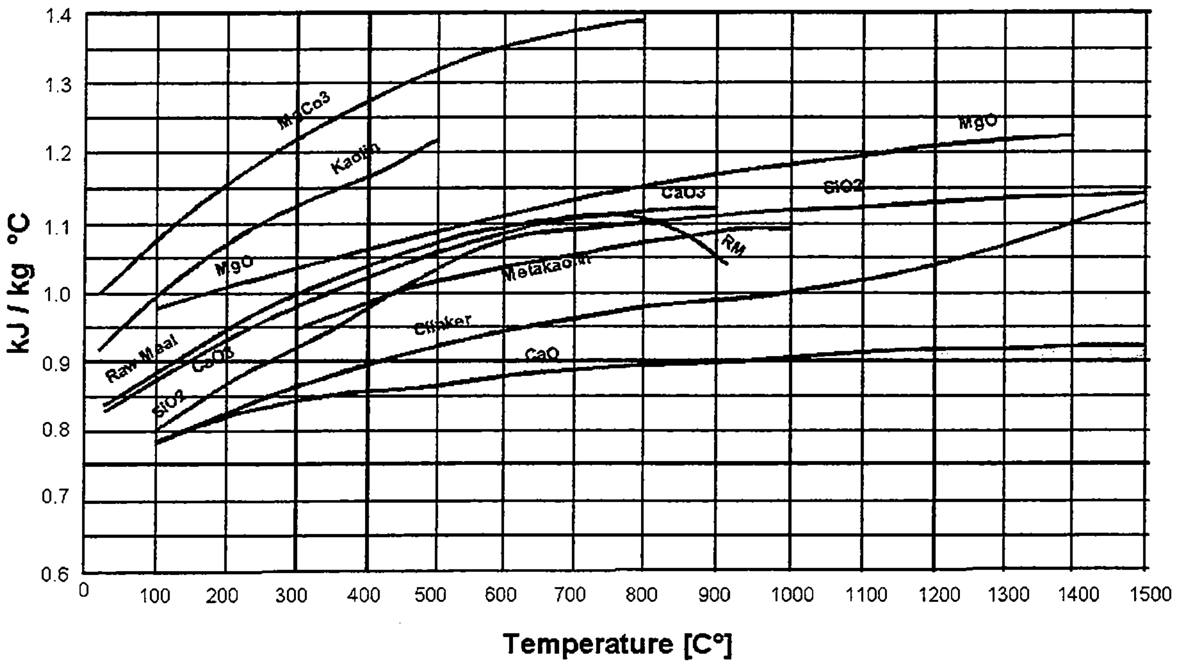


Fig. 6 c_p of Liquids and Fuels

Temp.	c_p of Liquid Water
0°C	4.22 kJ/kg C
50°C	4.18 kJ/kg C
100°C	4.22 kJ/kg C

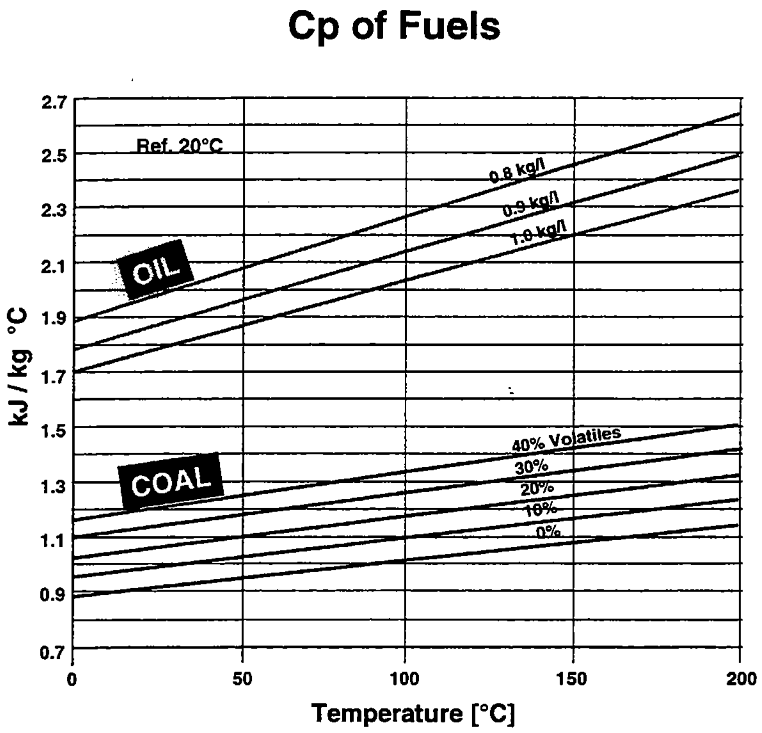
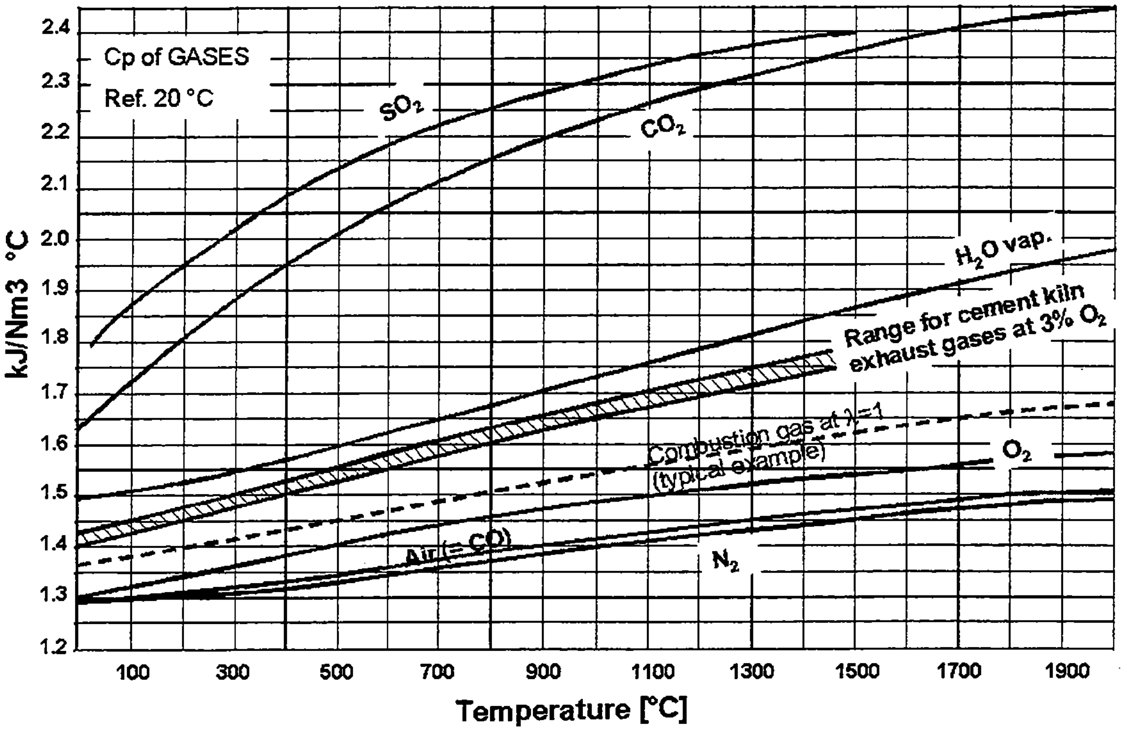


Fig. 7 **c_p of Gases**



4.9.2 Calculation of c_p of Mixtures

The c_p values are usually tabulated for pure substances. If a mixture is present it may become necessary to calculate the c_p starting from the given composition. This is better shown in a practical example (instead of a general formula):

Example:

Exhaust gas of suspension preheater kiln at 360 °C

- Measured by Orsat (dry):
    - CO_2 = 27.2% (CO = O)
    - O_2 = 4.3%
    - N_2 = 100 - 27.2 - 4.3 = 68.5%
- From moisture determination:
    - H_2O = 0.08 Nm^3/Nm^3 wet

What is the c_p value of the mixture (wet gas)?

	Dry Gas (Vol %)	**Wet Gas (Vol %)**	**c_p (pure (kJ/Nm^{3}C)**	**c_p x Vol. Frac. (kJ/Nm^{3}C)**
CO_2	27.2	25.0	1.92	0.480
O_2	4.3	4.0	1.37	0.055
N_2	68.5	63.0	1.31	0.825
H_2O	0	8.0	1.55	0.124
Total	100%	100%	-	$1.484 \cong 1.48$

Result: c_p of mixture = 1.48 kJ/Nm^{3}C (at 360°C)

The above value is typical for a normal SP kiln. We will always find values in the 1.5 kJ/Nm^{3}C range.

4.10 Heat Loss due to Radiation and Convection

4.10.1 General

In practice it is quite convenient to treat both, radiation and convection heat transfer together. Although the physical laws of these two heat transfer phenomenas are different they are usually given as a total.

The determination of total heat transfer coefficients by using simplified working diagrams will be accurate enough. Therefore the theory how to calculate the values is treated in separate chapters (6.3 and 6.4). The user of this chapter does usually not need to go into details of radiation and convection heat transfer theories. In addition, the calculation from the complete theory would hardly increase the practical accuracy, since all these theories contain a certain inaccuracy.

4.10.2 Radiation Heat Transfer

Radiation heat transfer depends on the surface temperature and the emissivity ε (0...1).

Typical values for ε:

Type of Surface	**Temperature °C**	ε
Rough oxidized steel	100	1
Rough oxidized steel	400	0.9
White lime paint (on steel)	400	0.8
Aluminium paint	100	0.2 to 0.4
Aluminium, rolled sheet metal	100 to 500	0.08
Aluminium, polished or bright foil	100 to 500	0.04

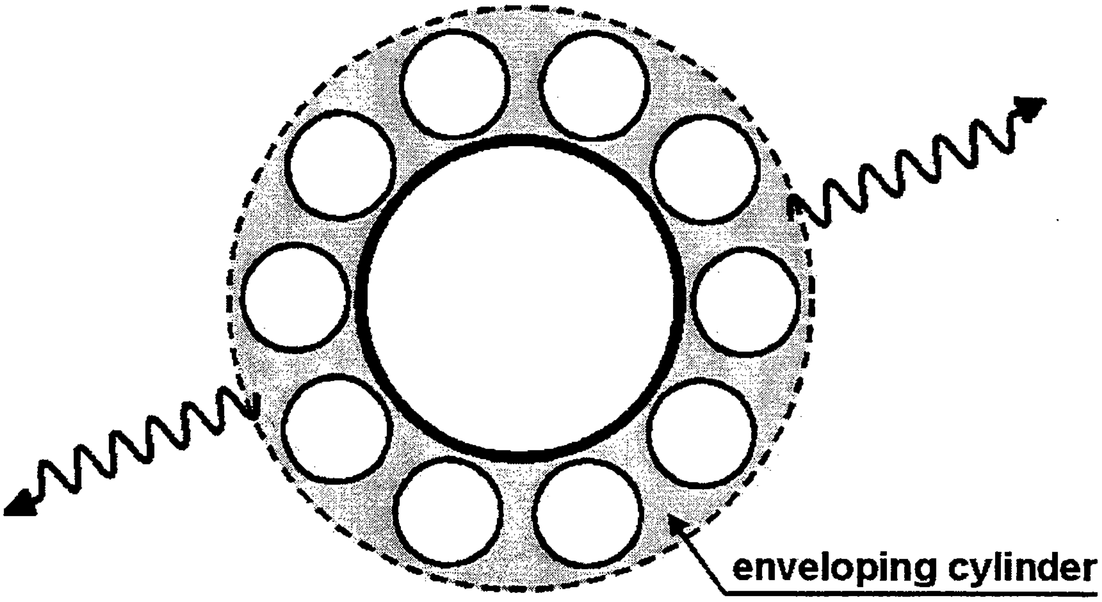
In most cases an ε value has to be set at the pyrometer used for the measurement (depending on the type).

For pyrometers giving readings for a constant emissivity $\varepsilon = 1$. Fig. 8 can be used for correction.

The pure radiation heat transfer coefficient α_{rad} (W/m^{2}C) is shown in Fig. 9.

Note that the temperature axis in Fig. 9 means temperature difference to ambient (same convention as for the following Fig. 10 and 11 - see paragraph 4.10.3 and 4.10.4).

Radiation heat transfer calculation does usually not create special problems as long as the radiating surfaces face freely towards ambient. A particular situation occurs on a planetary cooler where certain directions of radiation are shielded. That means not all areas are able for radiation towards the ambient.



Here, it would be obviously wrong to consider the total of the tube surfaces as radiation area. As a first approach the outer enveloping cylinder area (enveloping all tubes, see sketch) can be taken as reference area.

Fig. 8 **Relation between Emissivity ε and True and Apparent Surface Temperature**

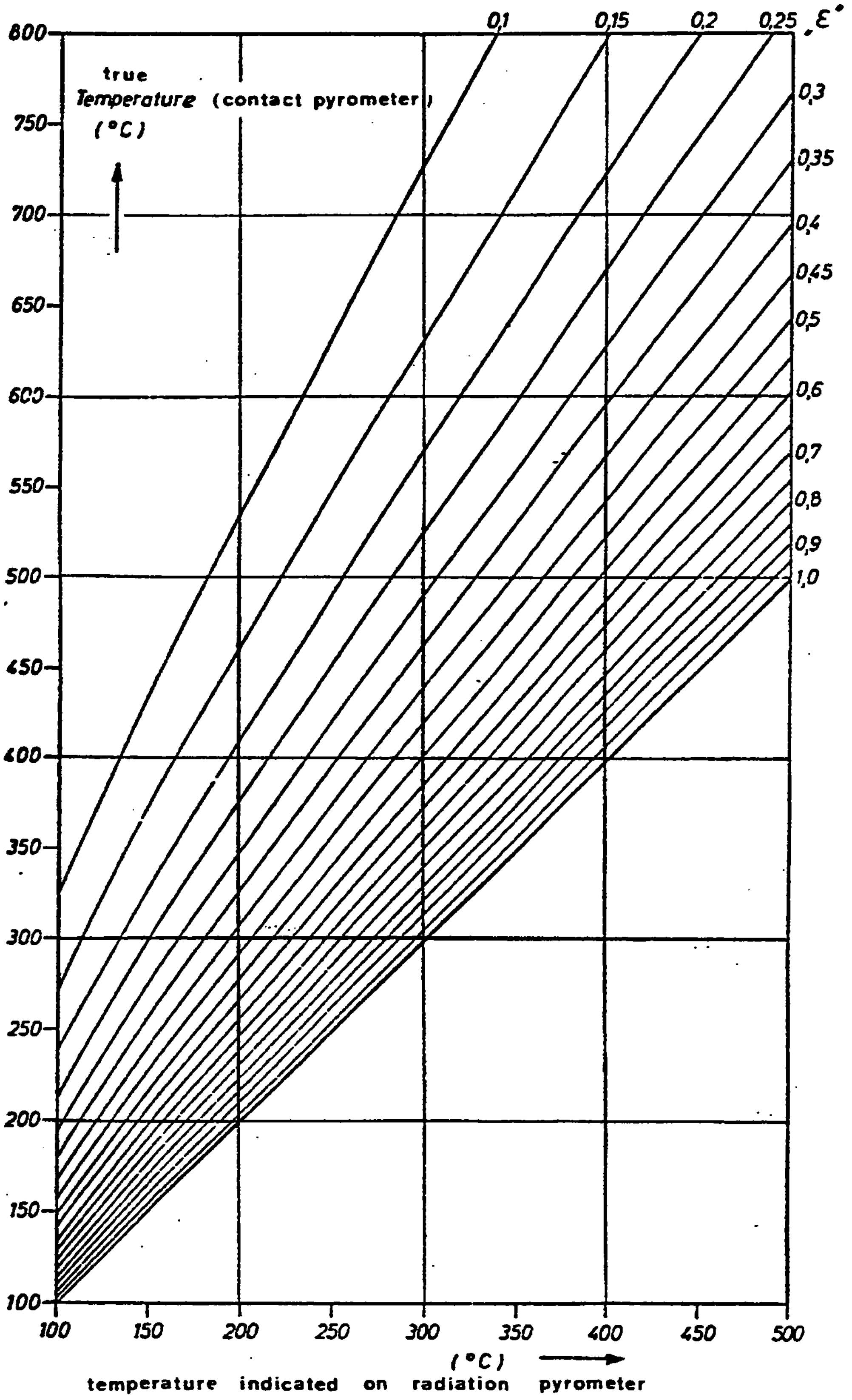
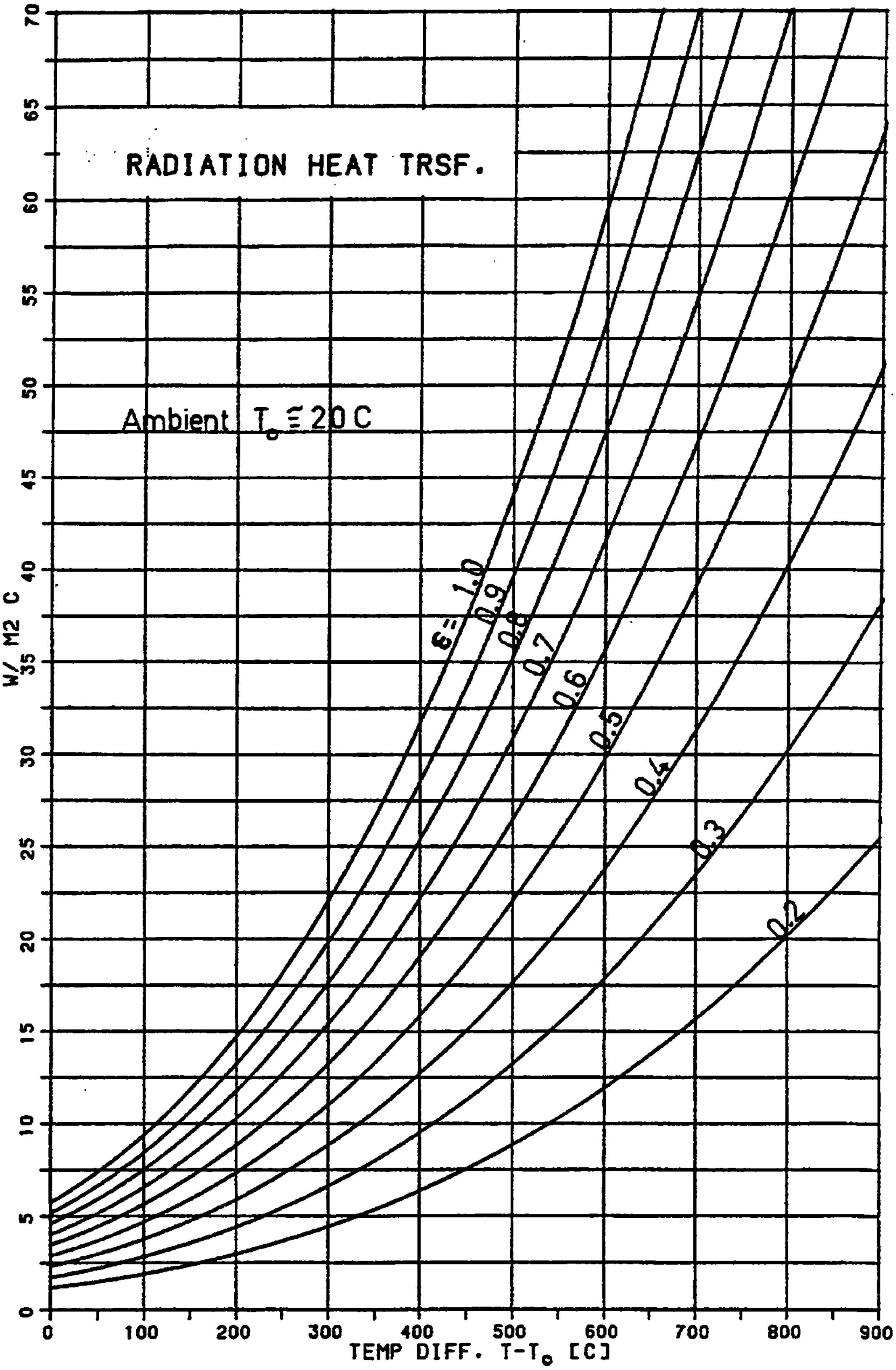


Fig. 9 **Radiation Heat Transfer Coefficient**



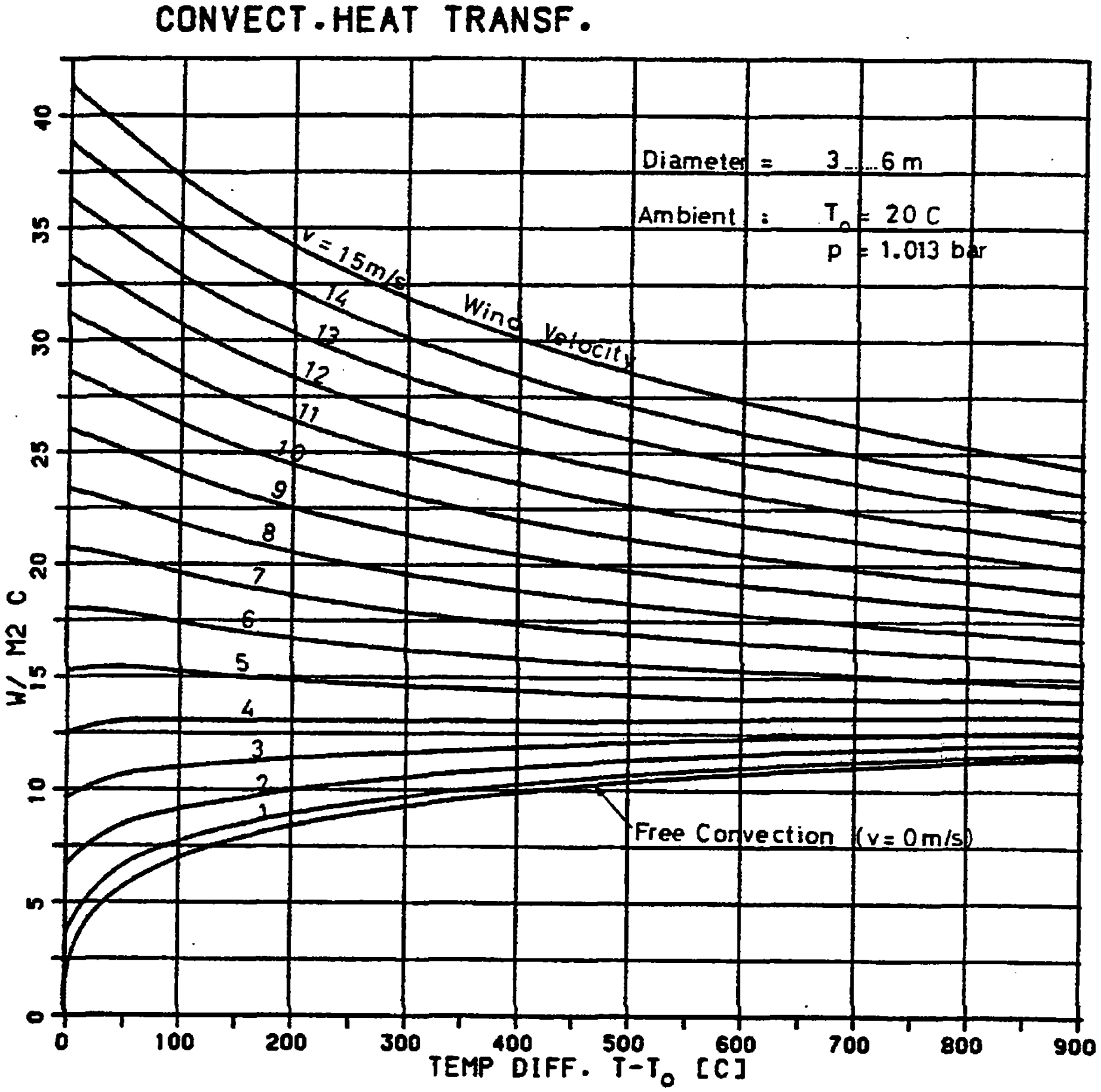
4.10.3 Convection Heat Transfer

Two different types of convection can be distinguished:

- Free convection (occurs by natural thermal draft, at low wind velocities)
- Forced convection (occurs at high wind velocities)

In practice an intermediate region between these two extreme cases can be encountered, depending on the wind velocity v (m/s). The resulting α_{conv} can be taken from Fig. 10.

Fig. 10 Convection Heat Transfer Coefficient



The diagram Fig. 10 refers to a normal kiln diameter range from 3 m to 6 m.

Note that the temperature axis in Fig. 10 means temperature difference to ambient, not temperature itself.

- Influence of diameter
  - Free convection (v = 0 m/s):
    - * The free convection coefficient is not depending on the diameter (or height) of equipment. If there is no wind Fig. 10 can be applied for any dimension.
  - Forced convection:
    - * In contrast to the free convection the forced convection does depend on the diameter. For this reason the application range of Fig. 10 is limited to 3 m...6 m, but only if high wind velocities occur. At low wind velocities no diameter limits exist.
    - * For very small tubes (or gas ducts) the following corrections of $\propto_{conv}$ (increases) can be made:

$$\left.\begin{array}{ll} \text{For } \varnothing \text{ 2 m} & +15\% \\ \text{For } \varnothing \text{ 1 m} & +30\% \\ \text{For } \varnothing \text{ 0.5 m} & +50\% \end{array}\right\} \quad \text{only at high wind velocities (min. 2 m/s)}$$

4.10.4 Total Heat Transfer Coefficient (Radiation and Convection)

For the determination of the total heat transfer coefficient $\propto_{tot}$ (W/m^{2}C) two cases are possible:

a) Standard Case

$\varepsilon = 0.9$ (rough oxidized steel surface)

This particular case is rather simple. Direct use of Fig. 11 is possible.

(Go into diagram with temperature difference and read out the total heat transfer coefficient.)

b) Non-standard Case

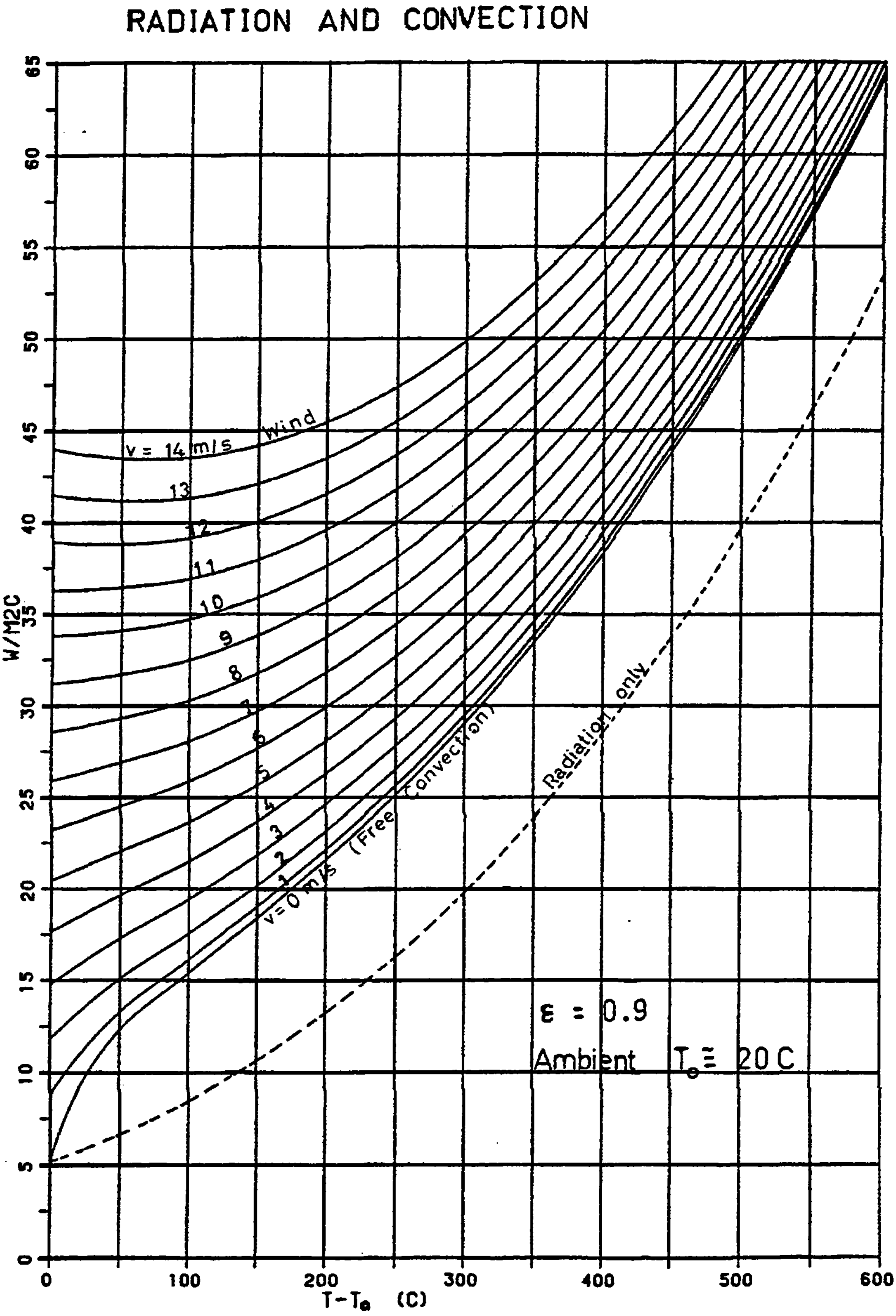
ε differs clearly from 0.9 and/or correction of convective heat transfer coefficient is necessary.

Make use of Fig. 9 and 10.

$\propto_{tot} = \propto_{rad} + \propto_{conv}$

(Caution: never add free convection + forced convection, Fig. 10 does already include the overlapping of both effects.)

Fig. 11 **Radiation and Convection Heat Transfer Coefficient (total)**



4.10.5 Total Heat Flow

The total heat flow from radiation and convection heat transfer is calculated according to:

Q_f = $\alpha_{tot} \cdot A \cdot (t - t_0)$ (W)

Q_f = heat flow (W); 1kW = 1000W

α_{tot} = $\alpha_{rad} + \alpha_{conv}$ = total heat transfer coefficient (W/m^2C)

A = shell area (m^2)

t = shell temperature (C)

t_0 = ambient temperature (C)

From the heat flow Q_f the specific loss can be calculated:

h = Q_f (kW) / m_f (t/h) · 3.6 (kJ/kg cli)

mf = clinker production (t/h)

3.6 = conversion factor, because of unit (t/h) for m_f

If the temperature of a shell area is not approximately constant it is necessary to subdivide the area into individual sections.

On a rotary kiln we may e.g. select about 10 (or more) individual cylindrical areas, each of them having the surface:

$$A_i = \Pi \cdot D_i \cdot L_i \quad (m^2)$$

Example:

- Rotary kiln
- Clinker production = 1900 t/d = 79.17 t/h
- ∅ 4.4 m x 67 m
- Average emissivity: $\varepsilon = 0.9$
- Ambient temperature = 20°C
- Average wind velocity v = 1 m/s (nearly free convection!)
- Shell temperature profile as indicated in the following table:

Length Position (m)	**Element Length (m)**	**Diameter (m)**	**Element Area [1] (m^2)**	**Surface Temp. (°C)**	**ε (-)**	**$\propto$ total[2] (W/m^2C)**	**Q_f (heat flow) (W)**
0 - 5	5	4.40	69.1	230	0.9	22.7	331'000
5 - 10	5	4.40	69.1	360	0.9	32.9	774'000
10 - 15	5	4.40	69.1	310	0.9	28.6	574'000
15 - 25	10	4.40	138.2	220	0.9	22.1	611'000
25 - 35	10	4.40	138.2	330	0.9	30.3	1'299'000
35 - 45	10	4.40	138.2	260	0.9	24.9	825'000
45 - 55	10	4.40	138.2	290	0.9	27.1	1'011'000
55 - 60	5	4.40	69.1	270	0.9	25.6	442'000
60 - 67	7	4.40	96.8	220	0.9	22.1	428'000
Total	**67 m**		**926.1 m^2**				**6'295'000 W**

Total heat loss = 6'295 kW

$$\text{Specific heat loss} = \frac{6'295 \cdot 3.6}{79.17 t/h} = \underline{286\ \text{kJ/kg cli}}$$

[1] A = ∏ . D . L (cylinder)

[2] radiation plus convection (see Fig. 11)

5. HEAT BALANCES

5.1 General

The results for heat inputs and outputs as calculated according to the preceding paragraph 4 are summarized in a balance sheet.

Table 1 (complete kiln system) and Table 2 (cooler only) are given as examples. They may also be used as checklist for completeness of own measurements and calculations.

- „Rest"-item:
  - A real balance (from complete date) will always include an item „rest", where all measuring errors (no measurement is 100% accurate) and non-considered items are included. The amount of the „rest" item should not exceed 3% of the total heat input.
- Heat consumption:
  - The actual heat consumption is the total of fuel input(s) which is not exactly the same as the total of heat inputs. If there are more than one fuel input, it is advantageous to indicate the actual (true) heat consumption separately.
- Cooler balance:
  - On a cooler, reliable measurement of secondary air heat is virtually impossible. Therefore, this value is determined by balance calculation and no rest item is given. The thermal efficiency of the cooler is usually defined as:

    $$\eta = \frac{\text{heat of secondary (and tertiary) air}}{\text{heat of hot clinker}} \quad (\%)$$

  - The % values in the balance sheet, however, are based on the total of inputs. This can cause a slight difference from the percentage of above η.

Table 1 Heat Balance of Cement Kiln System

(General case)

- All referred to 1 kg clinker
- Reference temperature = 20°C
- Ambient temperature = ... °C
- Production = ... t/h
- Specific heat cons. = ... kJ/kg cli

	Specifications	Temp.	Heat	
	(kg/kg cli), (Nm3/kg cli) (kW) etc.	(°C)	(kJ/kg cli)	(%)
INPUT				
Fuel combustion				
- primary firing		-		
- secondary firing		-		
Burnable matter in kiln feed		-		
Raw meal: sensible heat				
Fuel: sensible heat				
Primary air: sensible heat				
Cooler air: sensible heat				
CaO (non-carbonatic) in kiln feed		-		
Total of inputs		-		100%
OUTPUT				
Heat of formation	-	-		
Water evaporation:				
- kiln feed		-		
- water spray(s)		-		
Exhaust gas:				
- sensible heat				
- dust CaO-loss		-		
- unburnt gases (CO, etc.)		-		
Cooler: - waste air sensible heat				
- middle air sensible heat				
- clinker exit sensible heat				
Bypass losses: - sensible heat				
- dust sensible heat				
- dust CaO-loss		-		
- unburnt gases (CO, etc.)		-		
Radiation and Convection:	kW			
- preheater	kW			
- rotary kiln	kW			
- cooler	kW			
- tert. Air duct	kW			
Rest				
Total of outputs		-		100%

Table 2 Heat Balance of Clinker Grate Cooler

All referred to 1 kg clinker
Reference temperature = 20°C
Ambient temperature = ... °C

	Specifications	**Temp.**	**Heat**	
		(°C)	**(kJ/kg cli)**	**(%)**
INPUT				
Hot clinker				
Cooling air				
Total input				100%
OUTPUT				
Secondary air (incl. dust)				
Tertiary air				
Middle air				
Waste air				
Clinker outlet				
Water spray				
Radiation and convection				
Total output				100%

5.2 Examples of Heat Balances of Various Kiln Systems

Heat balances are given in Table 3 of various kiln systems. While comparing these it has to kept in mind, however, that kiln systems cannot only be judged based on these heat balances. The heat consumption of kiln system may depend on many items, those of major influence are:

- Kiln size, i.e. production rate
- Heat loss due to radiation and convection
- Secondary air quantity and temperature
- Operating conditions of kiln

Furthermore related systems have also to be taken into account. Consider a grate preheater kiln (Lepol kiln):

Its specific heat consumption may almost be as low as that of a 4-stage preheater kiln. However the grate preheater kiln, the semi-dry type, requires that additional heat is spent for material drying, whereas the exhaust gas of the 4-stage preheater kiln may be utilized to dry up to 8% water content of the raw material.

The table 3 gives heat balances of three different kiln systems.

- Wet kiln:
  - The wet kiln has a production capacity of approximately 3000 t/d. The slurry water content is 38%.
- Lepol kiln:
  - The heat balance of the Lepol kiln is of a comparatively small unit. The nodule moisture content is 12%. In general grate preheater kilns of the semi-dry type have a heat consumption only slightly higher than the 4-stage preheater kilns.
- Dry suspension preheater:
-
  - The heat balance of the 4-stage preheater kiln is typical for a unit in the 2000 to 3000 t/d range.

Table 3 Heat Balances of Wet, Grate Preheater and Preheater Kilns

	WET PROCESS		**SEMI-DRY (LEPOL)**		**DRY PRE-HEATER (4-STAGE)**	
	kJ/kg cli	**%**	**kJ/kg cli**	**%**	**kJ/kg cli**	**%**
1. INPUT						
FUEL						
from sensible heat	25	0.4	15	0.4	13	0.4
from combustion	5560	96.7	3343	97.6	3150	97.7
RAW MEAL						
from sensible heat	25	0.4	30	0.9	54	1.7
from sensible heat of water	71	0.2	17	0.5	-	-
COMBUSTION AIR						
from sensible heat of all the air supplied (prim. sec.)	67	1.2	20	0.6	6	0.2
TOTAL INPUT	5750	100	3425	100	3223	100
2. OUTPUT						
Heat of formation	1750	30.4	1750	51.1	1750	54.3
Evaporation of water from raw meal	2370	41.2	506	14.8	13	0.4
Exhaust gas sensible heat	754	13.1	314	9.2	636	19.7
Dust sensible heat	25	0.4	21	0.6	18	0.6
Incomplete combustion (CO)	-	-	-	-	-	-
Clinker exit temperature	59	1.0	50	1.5	63	2.0
Cooler exhaust gases	100	1.7	276	8.1	423	13.1
Losses due to radiation and convection	540	9.4	452	13.2	297	9.2
Water cooling (Recupol inlet chute)	-	-	42	1.2	-	-
Rest	152	2.6	14	0.4	23	0.7
TOTAL OUTPUT	5750	100	3425	100	3223	100

6. SPECIAL PART

6.1 Influence of Reference Temperature

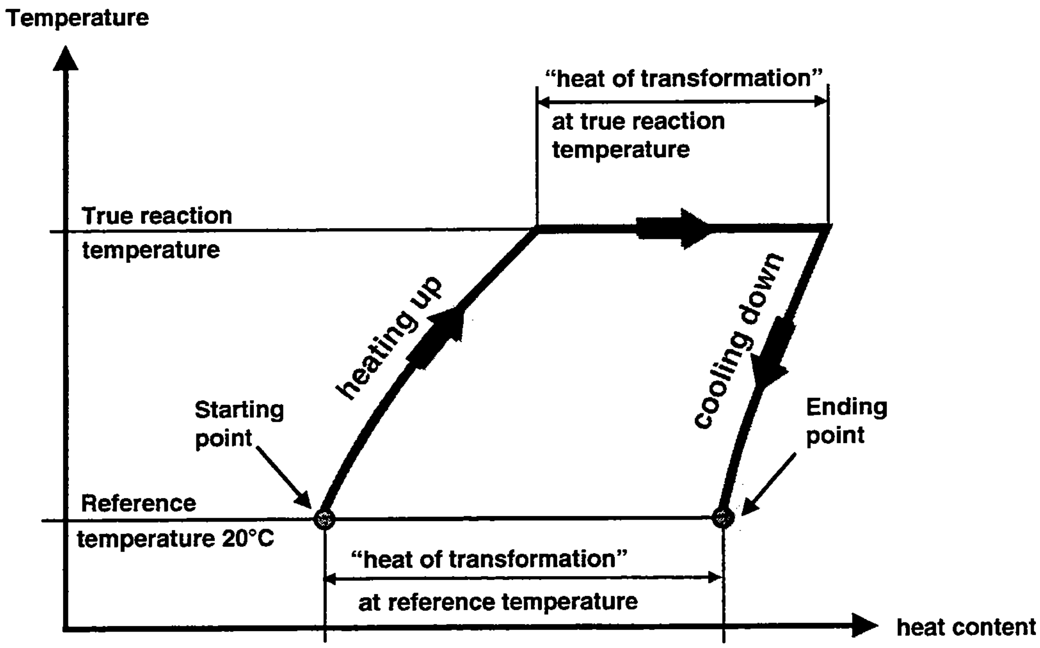
The reference temperature for a heat balance is usually set to 20°C. At this temperature all sensible heats become zero. This is quite practical because the normal ambient temperature is always near 20°C.

In addition the choice of the reference temperature has various other consequences which are normally not mentioned expressively. As long as the calculation procedure according to this chapter is applied we will not run into any practical problems. But if we want to go a bit deeper inside the matter we are soon confronted with some special questions as will be shown in the following.

6.1.1 „Heat of Transformation"

By the term „heat of transformation" we summarize here all heat effects by chemical reactions and changing of the physical state (combustion, heat of formation, evaporation). In order to understand the meaning of the reference temperature on these heat effects the following diagram is shown. It gives an example of an (ideal) isothermal process, including upheating and cooling.

Fig.12



We note from the diagram that the „heat of transformation" at reference temperature and at true reaction temperature are <u>not</u> identical. The reason is the different specific heat content of the starting material and the reaction products. It is also obvious that any other level for the reference temperature would basically change the „heat of transformation".

The „heat of transformation" at a reference temperature 20°C should therefore be seen in its proper sense: It is the heat effect under the convention, that we start at 20°C and end exactly at those 20°C. The real process (heating up, transformation, cooling) has <u>no</u> influence on the result, regardless of the true temperatures. This is a direct consequence of the principle of energy conservation.

Therefore, we may take into account that all „heats of transformation" which we use in a heat balance are based on reference temperature 20°C. Such values should not be confused with the heat effect at the true temperature of transformation or any other temperature.

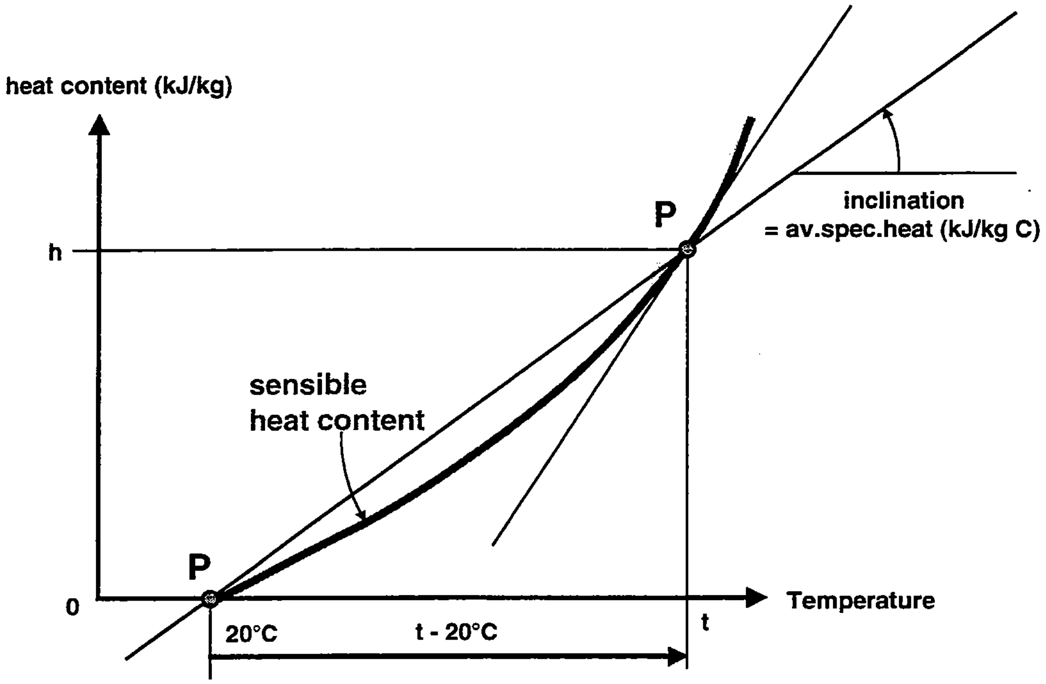
The items of interest are:

- Calorific value (combustion heat):
  - The CV must also be based on 20°C reference. The error which occurs when choosing a reference of e.g. 0°C is fortunately so small that it is within the normal accuracy of a CV determination.
- Heat of formation:
  - Regarding the heat of decarbonation only we may sometimes find values for the true reaction temperature (decarbonation, in the 800°C range). Such values shall <u>not</u> be used for a heat balance at 20°C reference, because this would produce an essential error!
- Heat of evaporation of water:
  - Note that we must use the evaporation heat at 20°C (2450 kJ/kg) in the balances and not the value at say 100°C (2260 kJ/kg). The effects of upheating of water or vapor are automatically considered by the normal balance calculation procedure (items for sensible heats).

6.1.2 Specific Heats

The specific heats used in this chapter are average values which are consequently based on 20°C reference temperature. We may illustrate this fact by an upheating process starting at 20°C as shown in the following graph:

Fig.13



The average specific heat can be graphically explained as the inclination of the straight line from P_0 to P. It is obvious that this inclination depends from the reference point P_0 at 20°C.

At the point P the tangent to the heat curve is also shown by a dotted line. The inclination of this line is the actual specific heat at the temperature t. This value is different from the average specific heat. Moreover, it does not depend from any reference point.

As a practical consequence we should never use specific heats from any source in the literature without checking what they really mean. In most cases actual values are given and not averages. Therefore, an integration or averaging would be required before we can use them for calculation of heat contents. Special caution should be made in the high temperature range where actual value and average value may be considerably different! In the 20° to 200°C range the practical differences, however, are rather small.

6.2 Heat of Formation

6.2.1 General

The heat of formation expresses the theoretical heat required for producing 1 kg of clinker. The following steps are taken into account:

		Approx. Temperature	**Heat Effect**
Step 1	Expelling of hydrate water (+ transformation of clay minerals)	~ 500°C	negative (heat consumed)
Step 2	Decarbonation of $MgCO_3$ (first) and $CaCO_3$ ($CaCO_3 \rightarrow CaO + CO_2$)	~ 850°C	negative (heat consumed)
Step 3	Formation of clinker minerals (C_2S, C_3S, C_3A, C_4AF)	~ 1400°C	positive (heat produced)

The net heat produced by the overall reaction is negative i.e. heat is consumed (listed as output).

The heat formation is defined at 20°C. In other words it expresses the theoretical amount of heat to transform raw meal at 20°C to 1 kg clinker at 20°C (if no heat losses would occur). It is therefore also considered as the theoretical minimum heat required for burning clinker.

The heat of formation is not at all depending on the way of the actual reaction (i.e. temperature versus time). The only precondition of course is that the reactions (step 1, 2, 3) have really been completed.

Although the basic principle of the heat of formation seems quite simple a few conventions (or definitions) are necessary here:

1) The hydrate water is expelled is considered as vapour (therefore no additional heat of evaporation has to be introduced into the balance!).
2) As a „standard case" the assumption is made that the CaO is present as $CaCO_3$ in the raw meal (in non carbonatic CaO occurs we do not change the heat of formation, but add heat inputs according to paragraph 4.7).
3) Burnable components in the raw mix are considered separately as inputs (see paragraph 4.4.2).

6.2.2 Calculation of Heat of Formation

6.2.2.1 Introduction

It is difficult to determine the heat of formation directly be calorimetric measurements. Therefore calculation methods have been developed in order to take into account the varying influences of raw mix properties.

Although formulas are given the following they should be applied with care. As long as the raw mix does not clearly deviate from the „standard" value of ~ 1750 kJ/kg the calculated figures must not necessarily give more accurate results than the 1750 kJ/kg.

Even extensive formulas for heat of formation contain a certain incertitude due to the partial lack of accurate thermodynamic standard values (for the minerals which are involved).

6.2.2.2 Calculation Formulas

The following formulas are partly based on the work of H. zur Strassen (Lit. 1) however a few recent adaptations have been made:

We will use the following notation:

CaO, MgO, SiO_2, Fe_2O_3, Al_2O_3 = Clinker analysis, expressed as weight fractions (kg/kg cli)

H_2O (kg/kg cli)= Hydrate water in raw material, referred to kg clinker (not to raw meal)

The following general formula for the heat of formation applies:

$$\boxed{h = CaO \cdot 3200 + MgO \cdot 2710 - SiO_2 \cdot 2140 - Fe_2O_3 \cdot 250 + \underline{h_{Res}} \qquad \text{(kJ/kg cli)}}$$

The last contribution „h_{Res}" depends on the Al_2O_3 and H_2O (hydrate) content. The calculation of „h_{Res}" depends on the information which is available on hydrate water and/or type of clay. Usually, the more information is known the better the result will be.

Case No.	**Hydrate Water (H_2O)**	**Type of Clay**	**Formula for h_{Res} (kJ/kg cli)**
1	not known	not known	$h_{Res} = Al_2O_3 . 1720$
2	known	not known	$h_{Res} = Al_2O_3 . 120$ $+ H_2O . 5520$
3	not known	known	$h_{Res} = (Al_2O_3)_K . 2220$ $+ (Al_2O_3)_M . 1310$ $+ (Al_2O_3)_I . 1640$
4	known	known	$h_{Res} = (Al_2O_3)_K . 1400$ $+ (Al_2O_3)_M . 620$ $+ (Al_2O_3)_I . 760$ $+ H_2O . 2450$

In case 3 and 4 a distinction has to be made from which type of clay the Al_2O_3 originates. The indices $_{K,\ M,\ I}$ denote:

K = Kaolinite

M = Montmorillonite

I = Illite

Note on the formulas for h_{Res}:

No. 1:
For general purposes, if no information on hydrate water available.

No. 2:
Takes into account the actual hydrate water content. It is also a very good approach if the hydrate water does not only originate from clays but for example from $Ca(OH)_2$.
Note that the coefficient for H_2O (hydrate) is more than twice the normal heat of evaporation $^{1)}$

Nos. 3 + 4:
Take into account the type of clay. (Hydrate water must originate from clay only, otherwise take No. 2).

When the CaO is introduced into the formula it is not required to know whether the CaO results from $CaCO_3$ or not. If any non carbonatic CaO is entering into the system we will take into account a balance heat input by definition (see paragraph 4.7) and therefore the calculated heat of formation is not affected.

1) The older formula from H. zur Strassen did allocate only 2450 kJ to H_2O, but instead 930 kJ to the Al_2O_3, which made it difficult to extrapolate it for other hydrates than from clay. It is certainly more logical to refer the heat to the H_2O, which is actually responsible for the heat consumption.

Examples

1) - Clinker composition:

CaO = 64.8 %
MgO = 1.2 %
SiO_2 = 22.6 %
Fe_2O_3 = 3.3 %
Al_2O_3 = 5.2 %

SO_3 = 0.52% TiO_2 = 0.29%
Na_2O = 0.08% Mn_2O_3 = 0.03%
K_2O = 1.20% L.o.I = 0.54%

- No information on hydrate water in raw meal available

$$h = 0.648 \cdot 3200 + 0.012 \cdot 2710 - 0.226 \cdot 2140 - 0.033 \cdot 250 + 0.052 \cdot 1720 = \underline{1704 \text{ kJ/kg cli}}$$

2) -Clinker composition:

CaO = 65.2 %
MgO = 1.2 %
SiO_2 = 22.9 %
Fe_2O_3 = 3.0 %
Al_2O_3 = 5.0 %

- Raw material = 1.1% hydrate water
R = 1.57 kg/kg → 0.017 kg hydrate water/kg clinker

$$h = 0.652 \cdot 3200 + 0.012 \cdot 2710 - 0.229 \cdot 2140 - 0.03 \cdot 250 + 0.050 \cdot 120 + 0.017 \cdot 5520 = \underline{1721 \text{ kJ/kg cli}}$$

6.2.2.3 Sulfatization Effects

The SO_2 can react with the alkalis K_2O or Na_2O (but also with CaO). For the heat effect the following (simplified) reaction is considered as typical:

$Na_2O + SO_2 + \frac{1}{2} O_2 \rightarrow Na_2SO_4 + \underline{\text{heat}}$

(molar heat effects of K_2O and Na_2O are of similar size!)

The overall degree of sulfatization reactions is usually not known. For the heat effect the following lower and upper boundaries can be calculated:

lower boundary = $- 8370 \cdot [(SO_3)_{cli} + (SO_3)_D - (SO_3)_R]$ (kJ/kg cli)
upper boundary = $- 10800 \cdot [(Na_2O)_R - (Na_2O)_{cli}]$
$- 7120 \cdot [(K_2O)_R - (K_2O)_{cli}]$
$+ 8370 \cdot [(SO_3)_R - (SO_3)_{cli}]$ (kJ/kg cli)

where SO_3, Na_2O, K_2O are expressed as <u>kg/kg cli</u> (referred to clinker!).

The indices denote: cli = in clinker
D = in dust
R = in raw meal

An average value can be introduced into the heat balance. Preferably this item is just listed under the item heat of formation (under output). Its sign is then negative, i.e. the outputs are reduced.

6.2.2.4 Lime Kilns

The formula for heat of formation of burnt lime is quite similar to that of cement clinker.

The following main reactions are taken into account:

$CaCO_3 \rightarrow CaO + CO_2$
$MgCO_3 \rightarrow MgO + CO_2$
$CaO + 2\,SiO_2 \rightarrow C_2S$ (dicalciumilicate)

Unlike on cement clinker the CaO in the lime product does not exclusively consist of „non carbonatic“ CaO, but some residual $CaCO_3$ is also present. Therefore the non carbonatic proportion CaO_{nc} has to be calculated first:

$CaO_{nc} = CaO_{tot} - CO_2 \cdot (56/44)$

The heat of formation becomes:

$h = CaO_{nc} \cdot 3150 + MgO \cdot 2710 - SiO_2 . 2100$ (kJ/kg lime)

CaO_{nc}, MgO, SiO_2 denote the weight fractions in lime product.

If the lime is present in lump form and the SiO_2 does originate e.g. from coal ash it is unlikely that C_2S mineral is formed. In such cases only the SiO_2 which comes from the limestone feed has to be considered in the formula.

6.3 Radiation Heat Transfer

The basic radiation formula is

Q_f = $C_R \cdot \varepsilon \cdot A\,[\,(T/100)^4 - (T_0/100)^4\,]$ [W]

Q_f = heat flow [W]
C_R = radiation constant = 5.67 W/m^2K^4
ε = emissivity (0...1)
A = radiating area (m2)
T = absolute temperature of radiating surface [K] (T = 273+t)
T_o = absolute temperature of ambient [K]

Strictly speaking above formula is only valid for cylinders of infinite length which radiate towards an ambient which is far away from the cylinder. No obstacles may shield off the radiation.

Though its simplifications this formula may be taken as a good approach for most cases.

By dividing Q_f by T - To and A, the ∝-value (heat transfer coefficient) can be obtained:

$$\alpha = \frac{C_R \cdot \varepsilon}{T - T_0}\left[\left(\frac{T}{100}\right)^4 - \left(\frac{T_0}{100}\right)^4\right] (W/m^2C)$$

Or alternatively the following formula, which is identical to the latter comes out:

$$\alpha = C_R \cdot \varepsilon \cdot \frac{4}{100}\left(\frac{\overline{T}}{100}\right)^3\left[1 + \frac{1}{4}\left(\frac{\Delta T}{\overline{T}}\right)^2\right] (W/m^2C)$$

$\overline{T} = \frac{T + T_0}{2}$ = average temperature (K)

$\Delta T = T - T_0$ = temperature difference (K or C)

From the second formula it becomes evident that (at small temperature differences) ∝ increases with the third (not fourth!) power of the average temperature. In addition, the ∝-value does converge towards a finite value at zero temperature difference.

For practical evaluation of the ∝ (radiation) Fig. 9 (see paragraph 4.10.2) is available. It is based on a constant ambient temperature of To = 293 K (20°).

If the true ambient temperature is actually not exactly 20°C one commits a slight error. Usually this can be neglected. In some extreme or exceptional cases the above formulas can be used for calculations.

Since the emissivity ε is often not known precisely and does also depend on the temperature it is usually not worthwhile to do small corrections on the ∝-values obtained from Fig. 9.

6.4 Convective Heat Transfer

6.4.1 Free Convection

Free convection occurs due to density differences between hot air (at the shell surface) and ambient air. A natural updraft causes a convective air movement.

For vertical plates or horizontal cylinders the following relationship applies:

$\underline{Nu = 0.13\ (Pr\ .\ Gr)^{1/3}}$ (-)

where: $Nu = \alpha D / \lambda =$ Nusselt number (-)

$Pr = c_p \eta / \lambda =$ Prandtl number (-)

$Gr = \dfrac{D^3 \cdot g \cdot \rho^2 \cdot \Delta T}{\eta^2 \cdot T_0} =$ Grashof number (-)

$\propto$	(W/m²K)	heat transfer coefficient
D	(m)	characteristical dimension *
λ	(W/mK)	heat conductivity
c_p	(J/kg K)	specific heat
g	(m/s²)	gravity constant = 9.81 m/s²
ρ	(kg/m³)	gas density
ΔT	(K)	temperature difference (T - To)
η	(kg/ms)	dynamic viscosity
To	(K)	absolute ambient temperature

* for a cylinder with diameter d → $D = (\Pi/2) \cdot d$

Application range: $Pr \cdot Gr > 10^9$

As long as there is a minimum temperature difference of a few degrees and the diameter range is over 1 m, above limitation does not affect the calculation.

A mathematical transformation of the basic equation reveals that the free convection heat transfer <u>does not at all depend on the characteristical dimension!</u> It follows:

$$\alpha = 0.13 \left(\frac{c_p \cdot \lambda^2 \cdot g \cdot \delta^2}{\eta} \right)^{\frac{1}{3}} \left(\frac{\Delta T}{T_0} \right)^{\frac{1}{3}} \ (W/m^2 K)$$

At ΔT = 0 the free convection becomes zero (which is different from the behavior of the radiation heat transfer!).

The numerical values for c_p, λ, ρ, η must be taken from tables for air at the average temperature between surface and ambient (use SI-units only).

Note that the density ρ depends also on the barometric pressure and therefore the result will depend on the altitude above sea level ($\propto \sim p^{2/3}$). As a general guideline the convective heat transfer drops by about 8% per 1000 m of altitude.

By using numerical approximations for the properties of air the following relationship has been developed (dimensional equation):

$$\underline{\alpha \cong 1.4 \cdot (\rho_0 \cdot \rho \cdot \Delta T)^{1/3}} \qquad (W/m^2K)$$

ρ_0 $(kg/m^3)=$ density at <u>ambient</u> temperature

ρ $(kg/m^3)=$ density at <u>average</u> temperature

Though its simplicity the latter formula covers the temperature range from 0...500°C with an accuracy of better than 1%! This is more than enough for practical purposes.

At sea level and at 20°C ambient it follows

$$\alpha \cong 1.6 \left(\frac{\Delta T}{1 + \frac{\Delta T}{2 \cdot T_0}} \right)^{\frac{1}{3}} \quad (W/m^2K)$$

Above relationship is also an excellent numerical approximation of the curve for v = O in Fig. 10 (see paragraph 4.10.3), which is actually based on complete computer calculations out of properties for air.

Table Properties of Air at Pressure = 1 bar

Temp. ϑ °C	ρ kg/m^3	c_p kJ/kg K	β 10^3/K	λ 10^3W/mK	η 10^6kg/ms	ν 10^6 m^2/s	α 10^6 m^2/s	Pr 1
-180	3.8515	1.071	11.701	9.0	6.44	1.67	2.18	0.77
-160	3.1258	1.036	9.320	10.9	7.85	2.51	3.37	0.75
-140	2.6391	1.021	7.758	12.7	9.20	3.48	4.71	0.74
-120	2.2867	1.014	6.659	14.6	10.49	4.587	6.30	0.73
-100	2.0186	1.011	5.846	16.4	11.72	5.806	8.04	0.72
-80	1.8073	1.009	5.219	18.16	12.89	7.132	9.96	0.72
-60	1.6364	1.007	4.719	19.83	14.02	8.567	12.0	0.71
-40	1.4952	1.006	4.304	21.45	15.09	10.09	14.3	0.71
-20	1.3765	1.006	3.962	23.01	16.15	11.73	16.6	0.71
0	1.2754	1.006	3.671	24.54	17.10	13.41	19.1	0.70
20	1.1881	1.007	3.419	26.03	17.98	15.13	21.8	0.70
40	1.1120	1.008	3.200	27.49	18.81	16.92	24.5	0.69
60	1.0452	1.009	3.007	28.94	19.73	18.88	27.4	0.69
80	0.9859	1.010	2.836	30.38	20.73	21.02	30.5	0.69
100	0.9329	1.012	2.684	31.81	21.60	23.15	33.7	0.69
120	0.8854	1.014	2.547	33.23	22.43	25.33	37.0	0.68
140	0.8425	1.017	2.423	34.66	23.19	27.53	40.5	0.68
160	0.8036	1.020	2.311	36.07	24.01	29.88	44.0	0.68
180	0.7681	1.023	2.209	37.49	24.91	32.43	47.7	0.68
200	0.7356	1.026	2.115	38.91	25.70	34.94	51.6	0.68
250	0.6653	1.035	1.912	42.43	27.40	41.18	61.6	0.67
300	0.6072	1.046	1.745	45.91	29.20	48.09	72.3	0.67
350	0.5585	1.057	1.605	49.31	30.90	55.33	83.5	0.66
400	0.5170	1.069	1.485	52.57	32.55	62.95	95.1	0.66
450	0.4813	1.081	1.383	55.64	34.00	70.64	107	0.66
500	0.4502	1.093	1.293	58.48	35.50	78.86	119	0.66
600	0.3986	1.116	1.145	63.5	38.30	96.08	143	0.67
700	0.3577	1.137	1.027	67.8	40.87	114.3	166	0.69
800	0.3243	1.155	0.932	71.3	43.32	133.6	190	0.70
900	0.2967	1.171	0.852	74.3	45.65	153.9	214	0.72
1000	0.2734	1.185	0.786	76.8	47.88	175.1	237	0.7

↓
(actual c_p, not average)

6.4.2 Forced Convection

Forced convection occurs at comparatively high wind velocity and dominates the convective heat transfer, i.e. the free convection is suppressed.

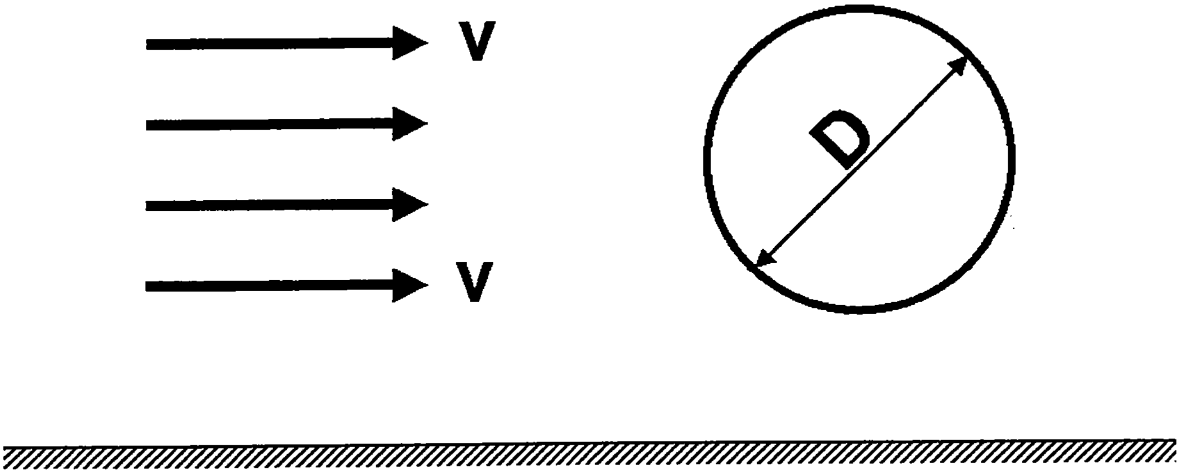
The calculation of forced convection is depending on many factors, such as:

- Wind velocity
- Direction of the wind
- Velocity distribution and flow obstacles
- Uniformity of wind
- Reynolds number (depends on kiln diameter).

There are a few more influence factors than in case of the free convection. Generally speaking the calculation of forced convection heat transfer contains more possible sources of error than free convection.

As a simplification, we will assume a cylinder in a non disturbed flow of a constant velocity v (at 90° against kiln axis).

Fig. 14



For air the following formula apply:

$Nu = 0.0239 \cdot Re^{0.805}$ for $Re =$ 40'000...400'000

$Nu = 0.00672 \cdot Re^{0.905}$ for $Re >$ 400'000

$$Re = \frac{vD}{\nu} = \frac{v \cdot D \cdot \rho}{\eta} = Re\,ynoldsNumber$$

$$Nu = \frac{\alpha D}{\lambda} = NusseltNumber$$

The properties η, λ, ϑ have to be taken at average air temperature.

There are other formulas in use which can give different results, the above formulas are preferred due to their simplicity. In any case there is always a incertitude from the mode of calculation itself.

Two main factors determine the ∝-value:

- Velocity v
- Average temperature (between surface and ambient)

In addition the ∝ does also depend on the diameter D. If the equation for high Reynolds number (Re > 400'000) is solved for ∝, the following relationship is obtained:

$$\propto \quad \underset{\substack{\downarrow \\ \text{proportional}}}{\sim} \quad D^{-0.095}$$

This means that the ∝ value does not much depend on D! Therefore it is possible to work with constant values within a certain diameter range.

This actually the base of Fig. 10 (see paragraph 4.10.3) which is calculated for a common range from 3...$\underline{4}$...6 m diameter.

6.4.3 Free Convection Plus Forced Convection

If the convection is clearly dominated either by free or forced convection the final determination of the representative ∝ does not give any problem, since the higher value has to be taken.

If the two values are of the same order they must be combined with an appropriate method. It would be certainly wrong to add the two values. A better approach is the square addition:

$$\alpha_{tot}=\sqrt{\alpha^{2}{}_{free}+\alpha^{2}{}_{forced}}$$

It is also valid if either the free convection or the forced convection dominates.

Fig. 10 is based on the above method.

6.5 Effect of Thermal Improvements

According to the actual condition of an existing kiln system (heat consumption, heat balance, other operating data) we can envisage an optimization campaign. From the thermal point of view we can take certain measures in order to reduce the specific heat consumption. For example:

- Better insulation of rotary kiln or preheater/precalciner in order to reduce radiation losses (except the sintering zone).
- Improvement of the cooler efficiency (optimization of grate cooler operation or installation of highly efficient internal equipment in planetary or rotary cooler).
- Reducing of false air inleaks at kiln seals or at preheater.
- Reducing of internal dust circulations in cooler, kiln or preheater (improves the internal counter-current heat transfer).
- Modification of raw mix in order to decrease the sintering temperature which in turn will also reduce heat losses. A further effect of such a measure can be the reduction of internal dust circulations due to better clinker granulometry (see above).
- Modification of raw mix in order to decrease the heat required for decarbonation, e.g. by making use of non-carbonatic CaO raw material sources. This possibility, however, is very rare and often not feasible. (Note the basic difference to the measures which tend to decrease the sintering temperature or increase the proportion of melting phase!)

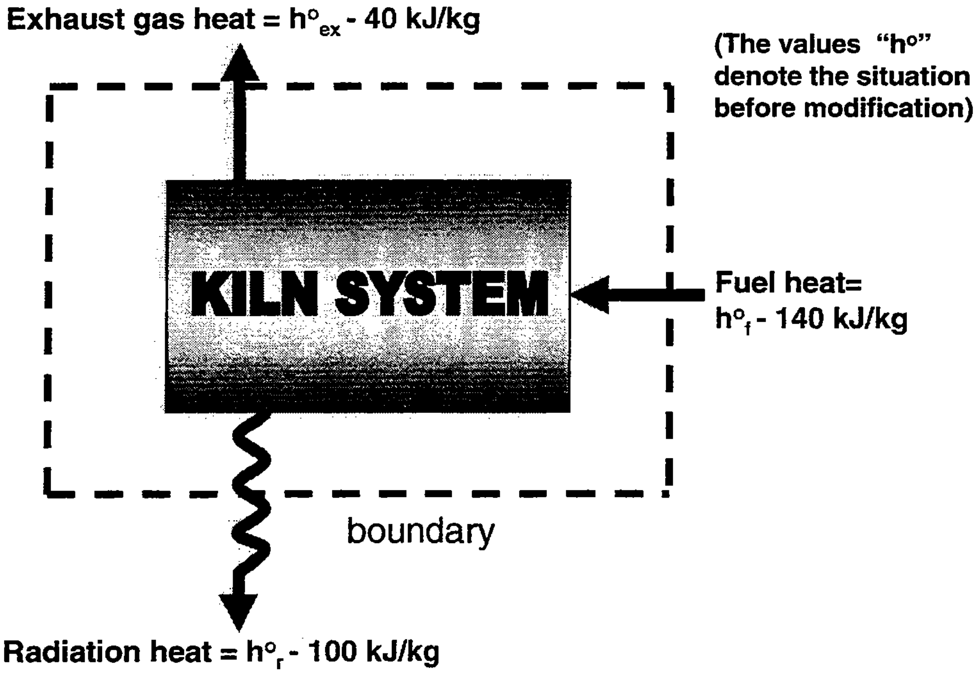
The above measures are just a few typical examples. When one goes into such items, an important phenomenon will appear soon: The so called „loss multiplication" factor for thermal losses (or savings). What does this mean?

If a saving (or loss) in the high temperature zone in a kiln of say 100 kJ occurs the possible gain in fuel heat consumption will not be 100 kJ but rather 130 to 150 kJ. That means that the primary saving (in terms of heat balance item) will be multiplied by a factor of up to 1.5.

At the first glance the above principle seems to be contradicious because it would violate the principle of heat balance or the energy law. However, what really happens is a differential change of more than only one heat balance item. To illustrate this fact we start from an example where we have reduced the shell radiation losses by 100 kJ/kg cli.

The following differential balance situation occurs:

Fig. 15



The corresponding multiplication factor for the above case is:

$$\text{multiplication factor} = \frac{-140\ \text{kJ/kg}}{-100\ \text{kJ/kg}} = \underline{1.40}$$

The above fact does result from the thermal behavior of the system and can be verified by simulation models (not by a simple balance only).

A factor in the 1.4-range is quite typical for the situation in the high temperature zone (above 800°C) of a cement kiln. The main effect of a change in this zone will be a corresponding change at the exhaust gas, but also other minor effects will occur (e.g. at cooler losses).

A "differential balance" of heat can still be applied according to:

Input Change	**Output Change**
fuel = - 140 kJ/kg	radiation = - 100 kJ/kg exhaust = - 40 kJ/kg
total = - 140 kJ/kg	total = - 140 kJ/kg

The principle of loss multiplication does not only apply for radiation in the high temperature zone but also for the heat which is recuperated in the clinker cooler.

Regarding the false air inleaks the corresponding deterioration of heat consumption is often under-estimated. If false air inleaks into the high temperature zone it does not only cause a heat loss because this air must be heated up to the exhaust gas temperature of the kiln system! It actually causes much more losses than what would result from such a simplified calculation approach. As a rule of thumb we may consider the following two main effects in order to come to a realistic result:

- Heating up of false air at the temperature of the high temperature zone which can be set approximately to 800°C (end of HT-zone).
- Multiplication of the above heat requirement by a loss multiplication factor.

The above calculation is a rough approach. By more sophisticated simulation models we find e.g. that a false air inleak into the high temperature zone of 0.08 Nm^3/kg cli can cause an additional heat consumption of 100 kJ/kg cli. In contrast, the inleak in the low temperature zone (e.g. air lift on SP-kiln) is much less critical.

6.6 Heat Transfer in Preheaters and Coolers and Improvement Potential

Normally we are considering a cement kiln as an equipment for burning cement clinker. As an essential feature we must be able to generate a high sintering temperature in the order of 1450°C (material temperature).

But a kiln system is of course much more than a generator of sintering temperature. It is also a system of heat exchangers which allows for burning at low heat consumption. Generally speaking we will find two essential heat-exchanging systems on any cement kiln:

a) raw meal preheater
b) clinker cooler

Low heat consumption is only possible if the above two „heat exchangers" perform optimally.

How can we get optimum heat exchange performance? Form the basic theory it is known that even in case of an exchanger which is perfectly insulated against ambient temperature influence, three important conditions are required for optimum heat exchange:

1) Optimum heat transfer rate (here: from gas to solid) → high specific contact or surface area, high $\propto$ (W/m^{2}C).
2) The two heat exchanging streams must flow in counter-current manner, or at least in an arrangement which has similar characteristics to a counter-current system (e.g. overall arrangement of a 4-stage cyclone preheater).

3) If we want to recover heat from a „flow 1“ completely into a „flow 2“ the „flow 2“ must have at least the same <u>heat equivalence</u> as „flow 1“:

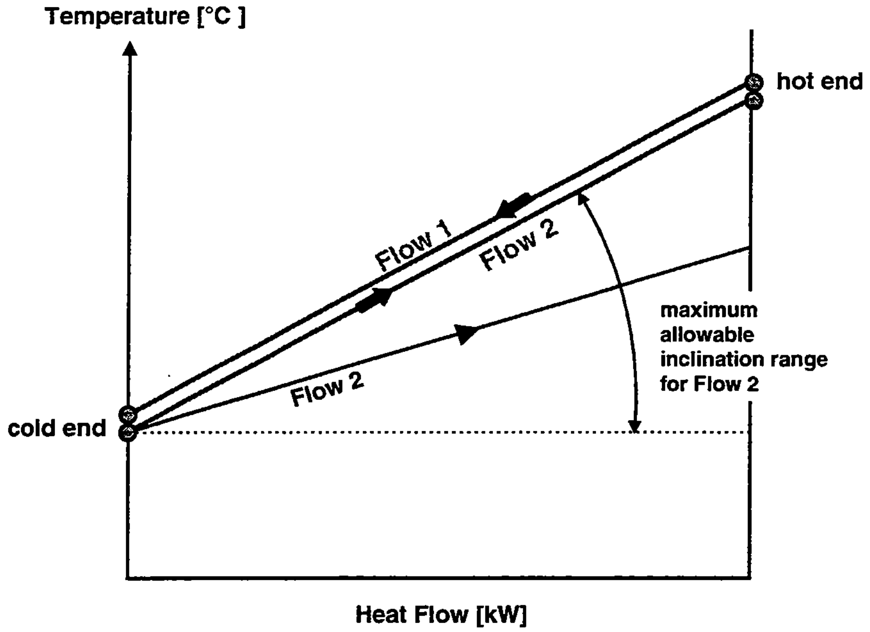
   <u>(flow 2) x (c_{p2}) ≥ (flow 1) x (c_{p1})</u> [kW/C] or [kJ/kg cli C]

   flow: [kg/s] or [kg/kg cli]

   cp: [kJ/kg C]

In the above equation the c_p values are considered as constant (approximation).

Graphically this means that the heat characteristic curves of the two heat flows must be in a certain relationship as shown here:



What are the practical consequences for a cement kiln? We consider:
  A) Raw meal preheater
  B) Clinker cooler

A) <u>Raw meal preheater</u>

1) Heat transfer rate:
   - Optimum heat transfer rate and optimum specific surface (small particles) and distribution has been almost achieved in the cyclone suspension preheater. After every cyclone stage material and gas come to almost complete temperature approach and there is usually little to improve on that.
   - Improvement are rather to be done where the heat exchange takes place in the rotary part itself. Especially on wet and long dry kilns the kiln internal fittings are essential for good heat exchange.

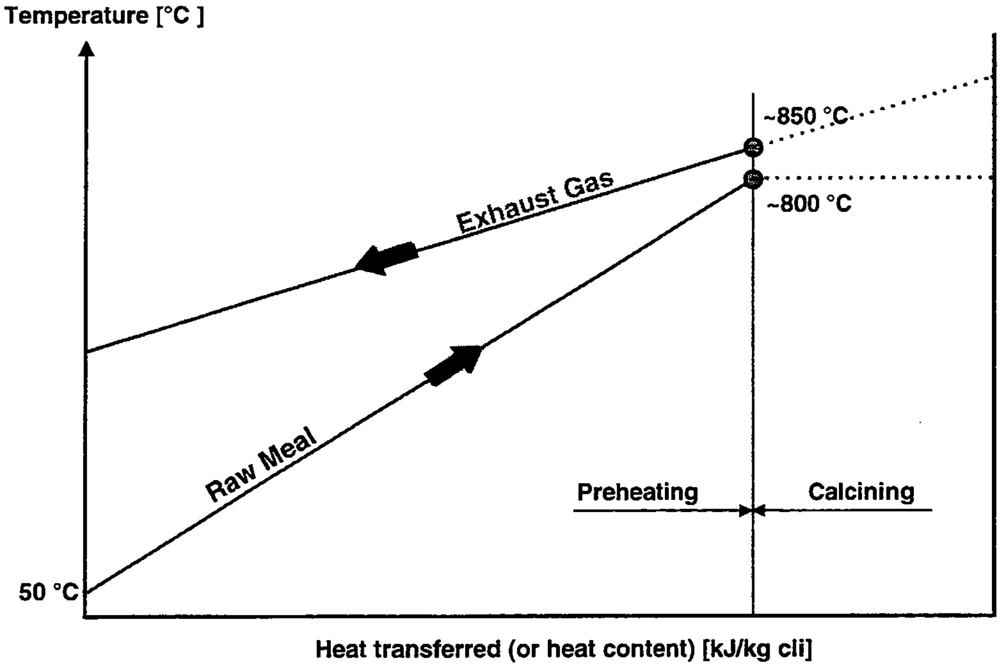
2) Counter-current principle:

- Counter-current flow in its proper sense does not exist in case of a cyclone suspension preheater. Instead, we have usually four co-current heat exchanging units, but the overall arrangement acts as counter-current system. To reach an ideal state one would have to apply an infinite number of cyclone stages. Practically the common arrangement of 4 or 5 stages can be considered as sufficient.
- True counter-current preheaters are shaft preheaters or preheating in long rotary kilns. Such preheaters would theoretically be ideal. Practically they are less efficient because of distribution problems and backmixing effect (internal material circulations) and comparatively high losses to outside (in case of a rotary kiln).

3) Equivalence of heat flow characteristics:

- A general feature of any raw meal preheater is the surplus of heat input by the hot gases. After the calcining step the hot gas has a temperature of approx. 850°C and the specific quantity is always above ~ 1.3 Nm^3/kg cli even in case of an optimum kiln system (4-stage SP kiln). This amount of heat is too much, it cannot be used completely for preheating of raw meal (~ 1.56 kg RM/kg cli) up to calcining temperature (~ 800°C). Therefore a certain amount of waste heat will occur even in an ideal case. Theoretically we should not exceed ~ 1 Nm^3/kg cli for ideal recuperation. Practically this cannot be realized, not even on modern kiln systems which produce comparatively little exhaust gas.
- Graphically we have the following heat situation in a raw meal preheater:

Fig. 16



Above diagram is simplified but typical for any preheater.

Because of the „heat surplus" of the exhaust gas it is not possible to achieve an ideal recuperation even at perfect counter-current heat transfer (e.g. infinite number of cyclone stages). The exhaust gas will always give a certain residual heat content.

Practically this means that all kind of improvements on the preheater have a limited potential. In the example of a 4-stage preheater kiln we can add a fifth stage which causes a reduction of about 100 kJ/kg cli in fuel heat consumption. More than 5 stages will bring only marginal economical point of view. *) Even at 5 stages we may check if the necessary investment and the (possible) increase of pressure drop can be justified by the local cost structure.

*) Instead of constructing more than 5 conventional cyclone stages one would prefer here „non-conventional" preheaters, such as the cross-suspension-preheater (two strings with cross flow of raw meals).

B) Clinker Coolers

1) Heat transfer rate:

- On a planetary or a rotary cooler we have the possibility to increase the heat transfer rate by installation of efficient internal equipment (tumblers, lifters) which increase the active heat transfer area by better moving and scattering of the clinker. If a cooler has worn out internal equipment or equipment of inadequate design we may realize a considerable potential for improvements. Improvements may also result from a more uniform clinker granulometry (less internal dust circulations).
- On a grate cooler we find quite a different situation. The real problem is not the heat transfer rate between a piece of clinker and the cooling air but rather the uniform air distribution through the clinker bed. Also here we may realize a considerable improvement (thick bed operation, mechanical modifications at inlet zone etc.).

2) Counter-current principle:

- There is an obvious difference between planetary/rotary coolers and the grate cooler:

- planetary / rotary	→	counter-current flow
- grate cooler	→	almost cross-current flow

- The grate cooler has a nearly cross-current performance and has therefore, from its principle, a limited heat recovery potential. Improvements are possible when air recirculation (of hot waste air) to the first grate section is applied in order to increase the heat content of the secondary air. Another quite different measure is the increasing of the bed thickness in order to come more towards a counter-current-like exchange (similar to a shaft cooler). The disadvantage is an increase of the cooling air pressure.

3) Equivalence of heat characteristic

- On a clinker cooler we would theoretically require approx. 0.77 Nm^3/kg cli of cooling air in order to transfer the clinker heat completely to the secondary air (under perfect counter-current heat exchange).
- The practical figures are usually above 0.8 Nm^3/kg cli. Compared to a raw meal preheater we have an inverse situation: The heat from the hot clinker could theoretically be completely recovered (under ideal conditions)! Of course, we know that the common, practical figures are often below 70%. The latter fact illustrates that from the basic principle there is still a considerable heat potential which is not used for reducing the kiln heat consumption.
- In this context it is also important to note that the practical efficiency of any type of clinker cooler increases with higher cooling air quantity. As a consequence we should draw as much cooling air as possible through the cooler and therefore avoid or reduce excessive primary air quantities or false air inleaks at the kiln hood or kiln seals. The improvement does not come from the heat transfer proper but rather from the improved „heat characteristic“ (air/clinker ratio).

7. TEST QUESTIONS

1) Give an example where it can be worthwhile to execute a complete heat balance on a kiln.
2) Summarize all important measurement points which are needed for doing a complete heat balance on a suspension preheater kiln.
3) What is the usual value (or range) for the specific heat (kJ/Nm^3 C) of exit gas of an SP-kiln at 350°C?
4) What is the sensible heat content of 1 kg clinker at 1450°C, expressed as kJ/kg cli?
5) What is the standard value (or range) for heat of formation (kJ/kg cli) for clinker burning? Which heat effects are included in above value?
6) Determine the heat transfer coefficient (W/m^{2}C) for the total heat transfer by radiation plus free convection. The temperature of the kiln shell section is 200°C (ambient = 20°C, $\varepsilon = 0.9$).
7) When has the forced convection heat transfer (instead of free convection) to be considered?
   How is the above value affected in case of smaller dimensions (say 1 m instead of 5 m diameter)?
8) If the shell losses in the calcining zone can be reduced by 50 kJ/kg cli, what will be the approximate saving of fuel heat (kJ/kg cli)?
9) What is the approximate fuel heat which can be saved through the installation of a fifth cyclone stage on a suspension preheater kiln?
   What would be the approximate amount of false air reduction (Nm^3/kg cli into the high temperature zone) in order to achieve a similar fuel heat saving?

8. LITERATURE

1) Zur Strassen, H.
Der theoretische Wärmebedarf des Zementbrandes
ZKG 10 (1957), Vol. 1, p. 1-12

1) Jakob, M.
Heat transfer, Vol. I (1949), p. 529

2) Hilpert, R.
Wärmeabgabe von geheizten Drähten und Rohren im Luftstrom
Forsch.-Ing.-Wes., Vol. 4 (1939), p. 215-224

3) Gygi, H.
Thermodynamics of the cement kiln, third industrial symposium on the chemistry of cement

4) Eigen, H.
Beitrag zur Thermodynamik des Drehofens
Tonindustrie-Zeitung 82 (1958), No. 16, p. 337-341

5) Frankenberger, R.
Beitrag zur Berechnung des Wärmeübergangs in Zementdrehöfen
Dissertation, Technische Universität Clausthal (1969)

6) Kühle, W.
Untersuchung über die äussere Wärmeabgabe von Drehöfen durch Strahlung und Konvektion
Zement-Kalk-Gips, Vol. 6, 1970, p. 263

7) VDZ Unterlagen
„Wärmetechnische Berechnungen“
Verein Deutscher Zementwerke E.V., Düsseldorf

8) VDI-Wärematlas
Berechnungsblätter für den Wäremübergang
VDI-Verlag GmbH, Düsseldorf

9) Barin, I. and Knacke, O.
Thermochemical properties of inorganic substances
Springer Verlag, Berlin, Heidelberg, New York

10) Elkajer, P. (FLS)
Die Bestimmung des Wärmeverbrauches mit vierstufigem Zyklonvorwärmer durch Aufstellung eines mathematischen Modelles
Zement-Kalk-Gips, Vol. 2, 1980

11) Gardeik, H.O.
Berechnung des Wandwärmeverlustes von Drehöfen und Mühlen
Zement-Kalk-Gips, Vol. 2, 1980

12) Rother, W.
Ausführung von Rohmehl-Wärmetauschern unter Berücksichtigung heutiger Kostenfaktoren
Zement-Kalk-Gips, Vol. 2, 1982, p. 66 ff.

9. SYMBOLS AND UNITS

A		m^2	area
C_R		W/m^2K^4	radiation constant
c_P		kJ/kg C	specific heat (at const. pressure),
	or	kJ/Nm^3 C	specific heat capacity
CV		kJ/kg	calorific value
D		m	diameter
g		m/s^2	gravity constant
h		kJ/kg	heat content (specific)
	or	kJ/Nm^3	
	or	kJ/kg cli	
L		m	length
m		kg	mass
	or	kg/kg	specific mass
m_f		kg/h	mass flow
Q_f		kW	heat flow (1 kW = 1 kJ/s)
t		C	temperature (Centigrade)
T		K	temperature (Kelvin)
v		m/s	velocity
w		kg/kg	water content
Greek Letters			
$\propto$		W/m^2K	heat transfer coefficient
ε		-	emissivity (for radiation)
λ		W/m C	heat conductivity
ρ		kg/m^3	density
Dimensionless Numbers			
Nu			Nusselt number (for heat transfer)
Pr			Prandtl number
R			kiln feed (raw meal) / clinker-ratio
Re			Reynolds number
Indices			
conv			convection
rad			radiation
tot			total
o			ambient condition or zero condition
Conversion Factors			
Length		1 inch	0.0254 m
		1 ft	0.3048 m
Area		1 sq. ft	0.092903 m^2
Volume, Volume Flow		1 cu.ft	0.028316 m^3
		1 cu.ft/min	1.699 m^3/h (actual m^3)
Mass		1 lb.	0.45359 kg
		1 short ton (USA)	907.185 kg

Pressure	1 bar	10^5 N/m^2
	1 atm.	1.013 bar
Energy	1 kJ	1000 J
	1 MJ	1000 kJ
	1 kWh	3600 kJ
	1 kcal	4.187 kJ
	1 BTU	1.055 kJ
Temperature Conversion	C =	5/9(F - 32)
	K =	273.15 + C
Heat Flow	1 kW	1000 W = 1 kJ/s
	1 kcal/h	1.163 W
	1 BTU/h	0.29307 W
Specific Heat	1 kcal/kg C	4.187 kJ/kg C = 4187 J/kg C
	1 BTU/lb F	1 kcal/kg C = 4.187 kJ/kg C
Heat Transfer Coeffic.	1 kcal/m^{2}h C	1.163 W/m^2 C
	1 BTU/ft^{2}h F	5.678 W/m^{2}C
Standard Conditions for Gases	Standard Conditions	0°C and 1 atm. (1.013 bar)

$$Nm^3 = act.m^3 \times \frac{2.73.15}{273.16 + t(c)} \times \frac{p(bar)}{1.013 bar}$$

Energy Balance of a Kiln

Calculation example

1. General kiln data

Supplier	Polysius
Type of process	4-stage suspension preheater
Start up	1975
Nominal Capacity	2'000 t/d
Kiln dimension	ϕ 4.6 x 70 m
Cooler type	planetary
Cooler tubes	9 x ϕ 2.0 x 19.8 m
Firing system	coal, indirect
Coal dosing	belt scale
Burner type	KHD/Pyrojet
Kiln feed system	air lift
Simplified flow sheet:	see attached sheet

2. Results of measurements

2.1 Mass and gas flows

Clinker (from weighing)	91.7 t/h (2'200 t/d)
Coal	10.5 t/h
Kiln feed	151 t/h
Dust in exhaust gas*	10 t/h
Air lift air	9'000 Nm^3/h
Total air into burner pipe	6'500 Nm^3/h
Exhaust gas after preheater	n.d. (to be determined by calculation!)
Water feed into planetary cooler (internal)	3 m^3/h

* collected in EP and weighed during direct operation

2.2 Results from laboratory

- Calorific value of coal (net, as fed to burner)	28'600 kJ/kg
- Moisture of kiln feed	0.6 %
- LOI of kiln feed	35.8 %

2.3 Gas analysis

At kiln inlet: O_2 = 1.5 %

At preheater exit: O_2 = 4.5 %
CO = n.d. (< 0.1 %)

2.4 Temperature measurements

- Gas temperature after preheater	370	°C
- Kiln feed (= air lift)	50	°C
- Clinker outlet (planetary cooler)	160	°C
- Air to burner (weighted average)	80	°C
- Ambient air	20	°C

2.5 Measurements of radiation and convection losses (by radiation pyrometer)

- Kiln shell losses, calculated section by section from shell temperature profile	4.8	MW
- Planetary cooler losses, calculated section by section from temperature profile of 9 tubes and by adequate assumption for reference are (outer envelope)	5.0	MW

- Preheater losses
  Because of comparatively uniform shell temperatures the following simplified approach can be applied:

Total of all surfaces (cyclones, riser pipes, ducts)	≈ 2'000	m^2
Average surface temperature	≈ 100	°C
Emissivity	≈ 0.9	
Wind velocity	≈ 1	m/s

3. Energy balance

Calculate the heat items according to course documentation and fill in the attached sheet "Energy balance of kiln".

ENERGY BALANCE OF KILN

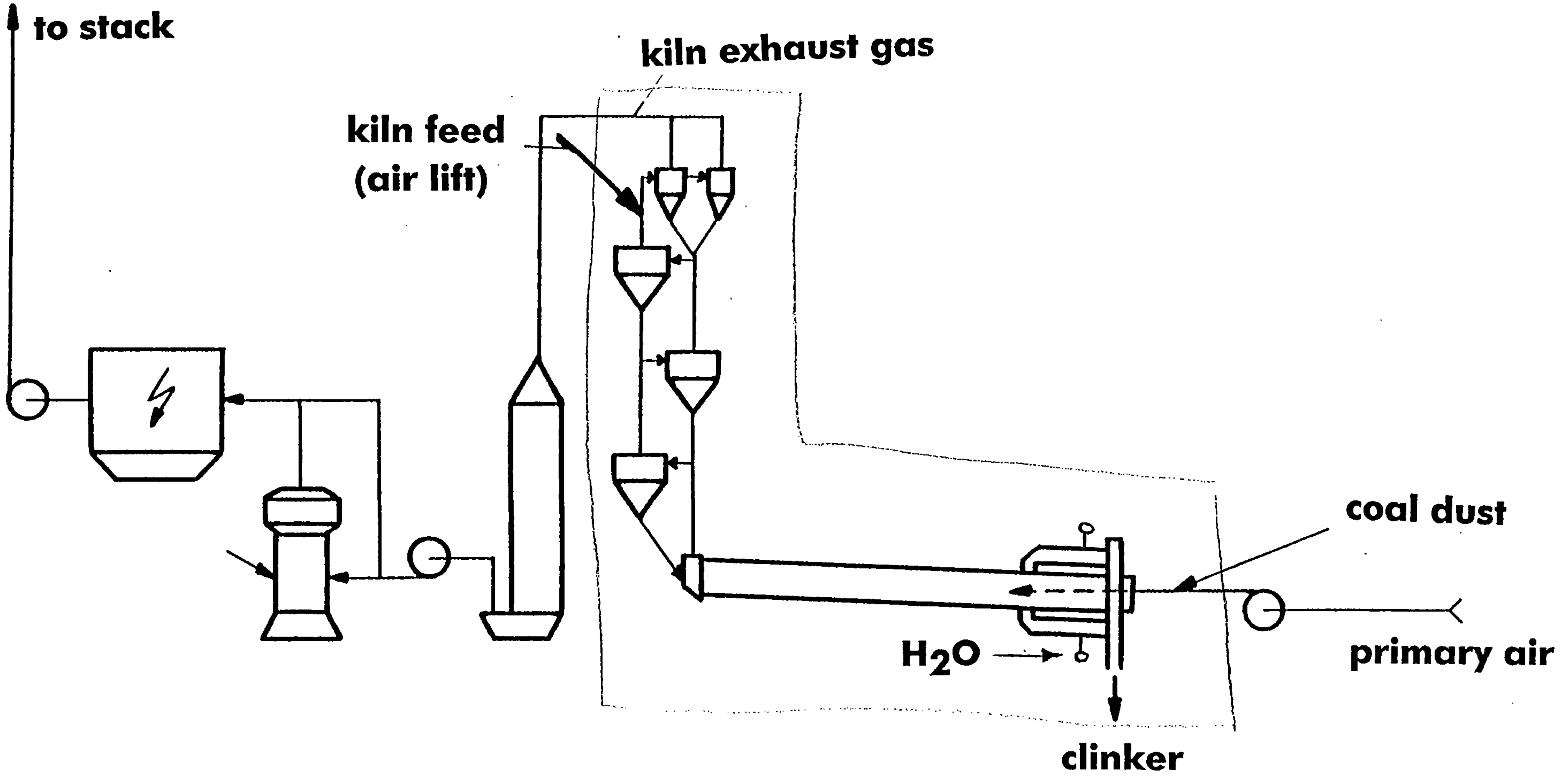
	Specifications	Temp. [°C]	Energy [kJ/kg cli]
INPUT Fuel combustion Primary air: sensible heat			3222.9 5.5
Kiln feed: sensible heat Air lift air: sensible heat			[illegible] 9.72
Total			
OUTPUT Heat of formation			[illegible]
Water evaporation: - kiln feed - cooler			[illegible] [illegible]
Exhaust gas: - sensible heat - dust sensible heat - CO-loss			[illegible]
Clinker ex cooler: - sensible heat			
Radiation and convection: - kiln - cooler - preheater			
Rest			
Total			

Reference: 20 °C

[illegible]

Energy Balance

Simplified Flow sheet



ENERGY BALANCE OF KILN (Solution)

	Specifications / Remarks	Temp. [°C]	Energy [kJ/kg cli]
INPUT			
Fuel combustion	0.1145 kg x 28'600 kJ	-	3'275
Primary air: sensible heat	0.071 Nm^3, c_p = 1.30 kJ/Nm^3C	80	6
Kiln feed: sensible heat	1.647 kg, c_p = 0.86 kJ/kg C	50	42
Air lift air: sensible heat	0.098 Nm^3	50	4
Total			**3'327**
OUTPUT			
Heat of formation	"standard case"	-	1'750
Water evaporation:			
- kiln feed	0.010 kg}	-	24
- cooler	0.033 kg} x 2'450 kJ/kg	-	80
Exhaust gas:			
- sensible heat	1.55 Nm^3 1),c_p = 1.51 kJ/Nm^3C	370	819
- dust sensible heat	0.109 kg, c_p = 1.03 kJ/kg C	370	39
- CO-loss	<0.0013 Nm^3(dry)x 12600kJ/Nm^3	-	(< 16)
Clinker ex cooler:			
- sensible heat	1 kg, c_p = 0.82 kJ/kg C	160	115
Radiation and convection:			
- kiln	4.8 MW	-	188
- cooler	5.0 MW	-	196
- preheater	2.4 MW 2)	(100)	94
Rest	-	-	22
Total			**3'327**

Reference: 20 °C

1) Calculation of exhaust gas at 4.5 % O_2

See paper combustion, gas flow and gas composition (Chapter 4.3.2)

- From combustion = 3.275 · 0.28 = 0.917 Nm^3/kg
- From raw meal (CO_2 + hydrate water) = 0.28 Nm^3/kg
- Excess + false air :

$$(3.275 \cdot 0.25 + 0.28) \frac{4.5}{21 - 4.5} = 0.300\ Nm^3/kg$$

- H_2O cooler and kiln feed = (0.033 + 0.010)/0.8 = 0.053 Nm^3/kg

Total exhaust gas = 1.550 Nm^3/kg cli

2) Calculation of radiation and convection losses of preheater

From Fig. 11

$$t - t_o = 80°C,\ \epsilon = 0.9\ v = 1 m/s \rightarrow \alpha = 15\ W/m^2C$$

$$Q = 2'000 \cdot (100 - 20) \cdot 15 = \underline{\underline{2'400\ kW}}$$

$$h = \frac{2'400 \cdot 3.6}{91.7\ t/h} = \underline{\underline{94\ kJ/kg\ cli}}$$

```
Heat losses of kiln shell (radiation and convection)         "Holderbank"
****************************************************           HMC VA/Ot
Plant :  Typical calculation example                             11.03.91
Date  :  11/3/91                                                    11:12

Kiln shell diameter [m]        4.6         Amb.temp. [C]             20
Kiln length         [m]         70         Abs.press [bar]         0.98
Tot.shell area      [m2]   1011.59         Air dens. [kg/m3]       1.17
Number of sections  [-]         30
                                           Emissivity[-]            0.9
Clinker production  [t/h]     91.7         Cr        [W/m2K4]      5.67


Pos. from outlet   Section   Shell     Temp.  Radiation  Conv.    Q tot
  From     To      length   section
  [m]      [m]      [m]      [m2]      [C]    [W/m2C]  [W/m2C]   [KW]
-------------------------------------------------------------------------

    0.0      2.4     2.40     34.68      211     12.69      8.13    137.9
    2.4      4.8     2.40     34.68      279     16.84      8.75    229.9
    4.8      7.2     2.40     34.68      283     17.11      8.78    236.2
    7.2      9.6     2.40     34.68      282     17.04      8.77    234.6
    9.6     12.0     2.40     34.68      247     14.78      8.48    183.1
   12.0     14.4     2.40     34.68      208     12.53      8.10    134.5
   14.4     16.8     2.40     34.68      166     10.41      7.58     91.1
   16.8     19.2     2.40     34.68      161     10.17      7.51     86.5
   19.2     21.6     2.40     34.68      191     11.63      7.90    115.9
   21.6     24.0     2.40     34.68      173     10.74      7.68     97.7
   24.0     26.4     2.40     34.68      303     18.52      8.93    269.4
   26.4     28.8     2.40     34.68      300     18.30      8.91    264.2
   28.8     31.2     2.40     34.68      261     15.66      8.60    202.8
   31.2     33.6     2.40     34.68      288     17.46      8.82    244.2
   33.6     36.0     2.40     34.68      248     14.84      8.49    184.5
   36.0     38.4     2.40     34.68      208     12.53      8.10    134.5
   38.4     40.8     2.40     34.68      180     11.08      7.77    104.6
   40.8     43.2     2.40     34.68      128      8.74      6.98     58.9
   43.2     45.6     2.40     34.68      233     13.94      8.35    164.7
   45.6     48.0     2.40     34.68      250     14.96      8.51    187.2
   48.0     50.4     2.40     34.68      239     14.30      8.41    172.4
   50.4     52.8     2.40     34.68      185     11.33      7.83    109.6
   52.8     55.2     2.40     34.68      246     14.72      8.47    181.8
   55.2     57.6     2.40     34.68      232     13.88      8.34    163.4
   57.6     60.0     2.40     34.68      230     13.76      8.32    160.9
   60.0     62.4     2.40     34.68      221     13.25      8.23    149.7
   62.4     64.8     2.40     34.68      224     13.42      8.26    153.4
   64.8     67.2     2.40     34.68      221     13.25      8.23    149.7
   67.2     69.6     2.40     34.68      241     14.42      8.43    175.1
   69.6     70.0     0.40      5.78      199     12.05      8.00     20.7

-------------------------------------------------------------------------
Total                70.00  1011.59                                4799.0
                 ******************                             *********
-------------------------------------------------------------------------
Minimum               0.40     5.78      128      8.74      6.98
Maximum               2.40    34.68      303     18.52      8.93
-------------------------------------------------------------------------
```

HEAT BALANCE OF SUSPENSION PREHEATER KILN WITH PLANETARY COOLER

PLANT Cement Course
KILN N° Example
DATE

Reference temperature	20 °C
Ambient temperature	20 °C
Ambient pressure	972 mbar
Production rate	91.7 t/h
Specific heat consumption	3275 kJ/kg cli

		SPECIFICATIONS			ENERGY		*)
		[kg/kg cli], [Nm3/kgcli] [ppm], etc.	LHV		[kJ/kg cli]	[kcal/kg cli]	
			cp [kJ/kg°C]	T [°C]			
INPUT							
Fuel	conventional fuel				3274.8	782.2	㉑
	alternative fuel						
	sensible heat						
Kiln feed	sensible heat	1.647	0.85	50	43.0	10.3	㉒
	combustible matter						
Primary air	sensible heat	0.071	1.299	80	5.5	1.3	㉓
Cooler	sensible heat of air	0.781			0.0	0.0	㉔
	sensible heat H2O		4.194	20	0.0	0.0	
Other input	air lift air	0.098	1.3	50	3.8	0.9	㉕
TOTAL OF INPUTS					3327.1	794.7	
OUTPUT							
Heat of clinker formation					1750.0	418.0	㉛
H2O evaporation	kiln feed	0.010	2450		24.2	5.8	㉜
	planetary cooler	0.033	2450		80.2	19.1	
Exhaust gas	sensible heat	1.549	1.513	370	820.2	195.9	㉝
	unburnt gases (CO)						
	dust	0.109	1.035	370	39.5	9.4	
Cooler clinker exit	sensible heat	1	0.809	160	113.3	27.1	㉞
Bypass losses	sensible heat						㉟
	unburnt gases (CO)						
dust	sensible heat						
	CaO (non carbonatic)						
Radiation & convection	preheater				94.0	22.5	㊱
	rotary kiln				188.0	44.9	
	planetary cooler				196.0	46.8	
Other output							㊲
Rest 0.7 %					21.8	5.2	㊳
TOTAL OF OUTPUTS					3327.1	794.7	

*) Remarks